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NPS-SCAT (Solar Cell Array Tester), the construction of NPS' first prototype Cubesat

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MONTEREY, CALIFORNIA

THESIS

NPS-SCAT (SOLAR CELL ARRAY TESTER), THE CONSTRUCTION OF NPS' FIRST PROTOTYPE CUBESAT

by

Alexander L. Bein

September 2008

Thesis Advisor: James H. Newman
Second Reader: Daniel J. Sakoda

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Large, expensive satellites have had failures or degraded missions due to solar cells that had not been tested in the space environment. To address these issues, a solar cell testing CubeSat prototype has been developed as part of the Space Systems Academic Group CubeSat program. This prototype provides a dedicated and responsive solution to testing solar cells in space and, as the first CubeSat built at NPS, it gives valuable experience that will encourage CubeSat projects at NPS in the future. This Master's Thesis describes the NPS-SCAT (solar cell array tester) project, including the author's experience as program manager of the project, responsible for budget, schedule and technical deliverables. This thesis explains in detail the process that was used to develop the prototype and gives recommendations for the flight unit. An important conclusion of this thesis is that CubeSats show great promise for hands-on education and as potential platforms to conduct focused research of national interest.

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**NPS-SCAT (SOLAR CELL ARRAY TESTER), THE CONSTRUCTION OF NPS'
FIRST PROTOTYPE CUBESAT**

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN SPACE SYSTEMS OPERATIONS

from the

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ABSTRACT

Large, expensive satellites have had failures or degraded missions due to solar cells that had not been tested in the space environment. To address these issues, a solar cell testing CubeSat prototype has been developed as part of the Space Systems Academic Group CubeSat program. This prototype provides a dedicated and responsive solution to testing solar cells in space and, as the first CubeSat built at NPS, it gives valuable experience that will encourage CubeSat projects at NPS in the future. This Master's Thesis describes the NPS-SCAT (solar cell array tester) project, including the author's experience as program manager of the project, responsible for budget, schedule and technical deliverables. This thesis explains in detail the process that was used to develop the prototype and gives recommendations for the flight unit. An important conclusion of this thesis is that CubeSats show great promise for hands-on education and as potential platforms to conduct focused research of national interest.

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ACKNOWLEDGMENTS

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I. INTRODUCTION

A. THE NEED FOR CUBESATS

Previous to CubeSats, access to space was costly and too technically intricate for most to participate. Each spacecraft design was, and to a large extent still is, specific to its payload. With no common bus or standard form factor, each spacecraft engineer had to recreate complex components. To get more people involved in spacecraft engineering and operations, a standard form factor, compatible with commercial-off-the-shelf (COTS) components, was needed to reduce complexity and cost. A standard form factor can also be leveraged for education. Satellites developed at educational institutions took many years to construct and launch. The long timeline meant students could only take part in a small portion of the entire process, leaving the educational impact diminished.

CubeSats are the answer to get small payloads into space quickly and relatively inexpensively. They reduce the complexity and cost with a standard form factor and compatibility with COTS components. Additionally, the shorter construction timeline is ideal for educational institutions. Students potentially can take part in the design, construction, launch and operation, getting the full educational experience within their short time span as a student.

Science and industry have a need for CubeSats. They provide a responsive and inexpensive way to perform one or more small experiments in the space environment. NASA, Boeing and the Aerospace Corp have all built CubeSats for this purpose, and the National Science Foundation is planning one also. Another benefit CubeSats bring to science and industry is training. They provide an inexpensive way to train our workforce in space engineering and space operations.
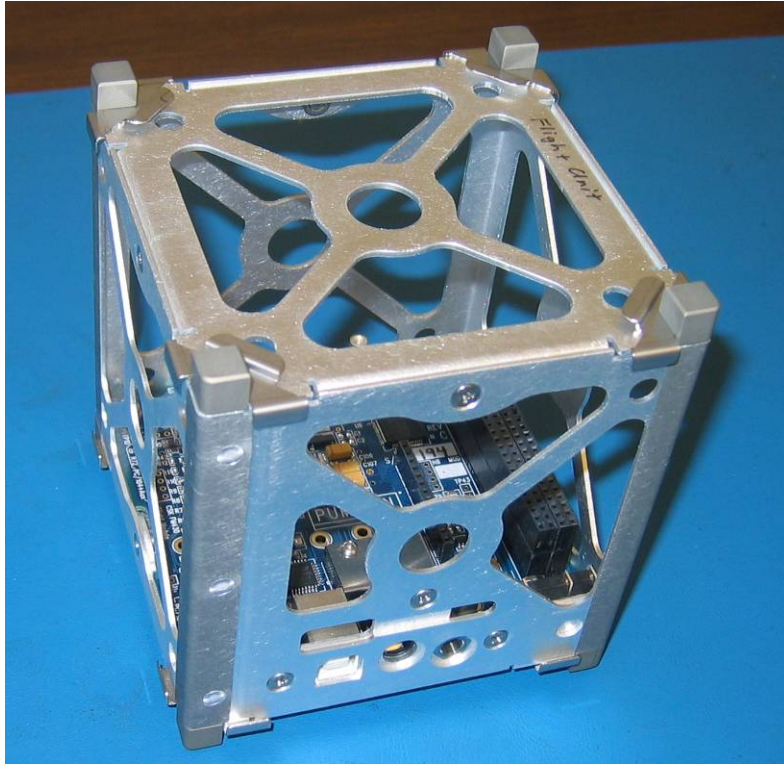
Figure 1.   Skeletonized CubeSat

B.   HISTORY OF CUBESAT

The CubeSat nano-satellite standard was first proposed by Professor Bob Twiggs from Stanford University in 1994 (news-service.stanford.edu/news/2001/january31/opal-131.html, accessed 24 July 2008). It is a 10cm X 10cm X 10cm, 1kg cube (see Figure 1) that augments extremely complex multi-million dollar satellites (www.cubesatkit.com, accessed 17 July 2008).   With the miniaturization of electronics, these liter-sized satellites can perform needed missions and experiments in the space environment for a fraction of the cost of larger satellites. CubeSats motivate student interest by providing achievable goals that result in many student-built satellites.

1.   CubeSat Partners

With CubeSat making important strides in opening up access to space, enablers are needed, such as CubeSat deployers and CubeSat COTS components.   California

Polytechnic State University (Cal Poly) rose to the challenge by providing viable CubeSat deployers with the Poly-Picosatellite Orbital Deployer or P-POD. The P-POD (Figure 2) is a rectangular box with a capacity of 3U worth of CubeSats. Its small size allows for easy integration on any launch vehicle. (See Figure 2. Photograph was found at cubesat.atl.calpoly.edu/media/P-POD%20Mk%20III%20ICD.pdf accessed 23 July 2008).

Figure 2.   P-POD built by Cal Poly

In 2000, CubeSat developers were trying to find a standard operating system that would accommodate the low power requirements of CubeSats when Andrew Kalman, the maker of Salvo Real Time Operating System (RTOS), offered a solution (www.pumpkininc.com, accessed 17 July 2008). His company began selling an operating system that was easy to use, efficient and it worked with CubeSats. Kalman noticed a growing demand for CubeSat components and realized there was not a single company filling that demand. Upon urging from Bob Twigs from Stanford, he set out to

create a comprehensive off-the-shelf CubeSat kit and now the inexpensive and versatile CubeSat Kit® is available to CubeSat engineers everywhere.

2. CubeSat Launches

As of August 2008, 40 CubeSats are known to have been launched, of which 24 successfully made it into orbit. There continues to be a large demand for CubeSat launches. Listed below are the launches that included CubeSat satellites adhering to the standard.

a. *Eurockot 2003*

The first CubeSats were launched from the Plesetsk Cosmodrome in Siberia on 30 June 2003. The launch was coordinated by the University of Toronto and included six CubeSats (cubesat.atl.calpoly.edu/pages/missions/eurockot-2003.php, accessed 29 July 2008).

b. *SSETI Express 2005*

Three more CubeSats were launched from the Plesetsk Cosmodrome in Siberia on 27 Oct 2005 (cubesat.atl.calpoly.edu/pages/missions/sseti-express-2005.php, accessed 29 July 2008).

c. *M-V-8 Launch 2006*

On 21 February 2006, Cute-1.7+ADP was launched from the Uchinoura Space Center in Japan (cubesat.atl.calpoly.edu/pages/missions/m-v-8-2006.php, accessed 29 July 2008).

d. *Dneper Launch 1 2006*

Fourteen CubeSats in five P-PODs were unsuccessfully launched from Russia on 26 July 2006 (cubesat.atl.calpoly.edu/pages/missions/dnepr-launch-1.php, accessed 29 July 2008).

e. GeneSat Launch 2006

NASA's GeneSat was launched 16 Dec 2006 from Wallops Island. This has been the only CubeSat launched from the United States, and it was launched from an Air Force Rocket. GeneSat was the first CubeSat to carry a biological payload into space (cubesat.atl.calpoly.edu/pages/missions/genesat-1.php, accessed 29 July 2008).

f. Dneper Launch 2 2007

Seven CubeSats on three P-PODs were launched from Baikonur Cosmodrome in Kazakhstan on 17 April 2007 (cubesat.atl.calpoly.edu/pages/missions/dnepr-launch-2.php, accessed 29 July 2008).

g. PLSV-C9 Launch

Six CubeSats were launched on 28 April 2008 from Sriharikota, India. One of the six successful CubeSats is Delphi-C3, a 3U CubeSat from the Netherlands that is testing thin film solar cells and an autonomous sun-sensor (www.delfic3.nl/index.php?option=com_frontpage&Itemid=1, accessed 31 July 2008).

h. Falcon 1

Two NASA CubeSats, NANOSAIL-D and PRESAT, were unsuccessfully launched on 03 August 2008 from Omelek Island (http://www.mister-info.com/?cmd=displaystory&story_id=11117&format=html, accessed 02 September 2008).

Launch	Date	# CubeSats	Location
Eurockot	30-Jun-03	6	Plesetsk
SSETI Express	27-Oct-05	3	Plesetsk
M-V-8 Launch	21-Feb-06	1	Uchinoura
Dnepr Launch 1	26-Jul-06	14	Baikonur
GeneSat	16-Dec-06	1	Wallops Island
Dnepr Launch 2	17-Apr-07	7	Baikonur
PLSV-C9	28-Apr-08	6	Sriharikota
Falcon 1	3-Aug-08	2	Omelek

Table 1.   CubeSat Launch History

C. NPS' DEVELOPING RELATIONSHIP WITH CUBESATS

1. Small Satellite Heritage

The Naval Postgraduate School has been involved in developing small satellites for years. PANSAT (Petite Amateur Navy Satellite) was developed and launched on 29 October 1998. The satellite provided a global, digital messaging system using spread spectrum techniques in the amateur radio 70 cm band. Most importantly, its development exposed many NPS students to satellite design, construction, launch and operations.

After PANSAT, the SSAG began development of NPSAT1 (Naval Postgraduate School Satellite) with several different experiments. Although nearing completion, the time to develop NPSAT1 has been extended several times because of the immense complexity of developing every system of the satellite along with multiple payloads. This long development timeline has not allowed NPS students to experience the full lifecycle of satellite construction and operation because they only study two to three years until they must transfer to their next assignment. The SSAG sees the benefit of enlisting CubeSats to help develop military space professionals and educate its students. A CubeSat potentially can be designed, constructed, launched and operated within a student's assignment at NPS. The experience NPS has with other spacecraft should enable the CubeSat program to flourish.

2. Naval Postgraduate School Solar Cell Array Tester (NPS-SCAT)

For the first CubeSat, a single experiment was desired to prove the CubeSat concept and to get experience building CubeSats. To reduce the complexity of building the first NPS CubeSat, a payload was proposed that had already been developed at NPS. One of the experiments on NPSAT1, a solar cell tester, would be the perfect experiment for a CubeSat. It is not too complex, it is small, does not require a lot of power, and the solar cell measurement system had already been developed. Additionally, there is a need

for NPS-SCAT because there are always new solar cells being developed that need to be tested in the space environment. This CubeSat is the focus of this thesis and the prototype is shown in Figure 3.
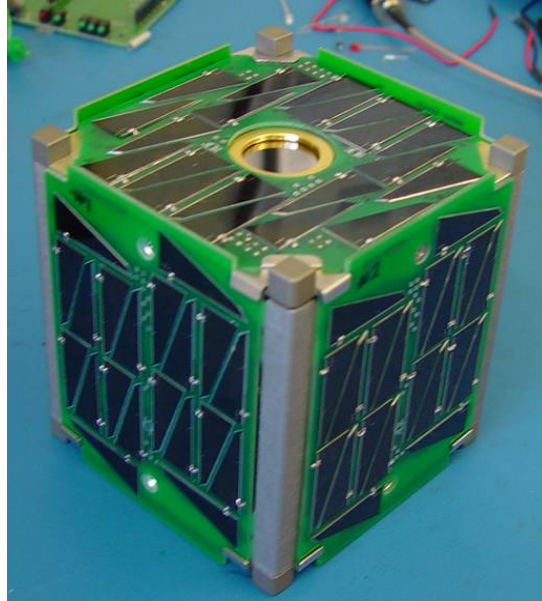
Figure 3.   NPS-SCAT

3.   Naval Postgraduate School CubeSat Launcher (NPSCuL)

With the burgeoning growth of CubeSats in the U.S.A., it is a missed opportunity that they are launched almost exclusively outside the United States. They are so small and light that they could be easily integrated on any launch platform. The problem CubeSats are running into in this country is the added risk they bring to the larger programs. Program managers for DoD systems have avoided that risk by not integrating CubeSats on their rockets. To alleviate that perceived risk, NPS is developing an EELV (Evolved Expendable Launch Vehicle) Secondary Payload Adapter (ESPA) compatible CubeSat launcher (NPSCuL, pronounced NPS "cool").

The ESPA Ring can accommodate up to six secondary payloads of up to 400 lbs each. United Launch Alliance is working with the Air Force to make ESPA rings standard on all U.S. launches with excess capacity to help promote the launch of small

satellites and experiments (Iannotta). NPS is taking advantage of this new requirement and is teaming up with Cal Poly to bring a CubeSat launch capability within the United States.

NPSCuL will have up to 50U worth of capacity in its ten 5U P-POD configuration. One full launch would equal the capacity of all the CubeSats that have made it to space in the first five years of CubeSats. This new capacity will assure more CubeSat developers of a launch and will spur on greater numbers of CubeSats, thus training more satellite engineers and perhaps revitalizing interest in space.

4. Tiny Spacecraft Assembly, Reconfiguration and Proxy-ops (TISARP)

TISARP is a design-in-progress at NPS of a reconfigurable CubeSat being developed by Professor Romano's group. In theory, it will be launched as a 5U CubeSat. After deployment, the top two cubes separate and independently reattach themselves making a T-shaped satellite. The experience gained in attitude control, control algorithms, and propulsion will open up many options for future space projects.

5. Tiny Scope

Also from Professor Romano's group, Tiny Scope is a 5U CubeSat design that explores the use of CubeSats for optical remote sensing. Using a cassegrain mirror, it will be able to image the earth at a resolution of 2.7m for its reference altitude of 500km (Blocker, 2). If this design proves feasible, cost savings for a tactical constellation could be tremendous and the operational benefit would be extremely valuable.

6. CubeSat Design Projects

Within the NPS curriculum there have been several design projects that have explored the feasibility of using CubeSats to conduct missions of national interest. One project is the design of a CubeSat constellation that could provide worldwide maritime domain awareness. Another project involves a CubeSat constellation that could provide

global imagery at 1m resolution. Another project is a CubeSat design that would be a diagnostics tool or a "black box" data recorder for a larger satellite.

D.   OBJECTIVE OF THIS THESIS

This master's thesis will discuss in depth the construction and operation of a solar cell testing CubeSat prototype. The NPS-SCAT prototype is a 1U CubeSat designed to test solar cells remotely and transmit the data to the ground station. One of its six faces will have experimental solar cells, a sun sensor and temperature sensors. The CubeSat is using a Microhard MHX 2420 radio, which integrates with the CubeSat Command and Data Handling (C&DH) board. The power system is a Pumpkin® linear power supply, which consists of two lithium ion IPOD batteries. The solar cell measurement system consists of eight experimental triangular advanced solar cells (TASC), a sun sensor, a temperature sensor and the electronics board to measure the solar radiation received by the cell. This combined information will be made into a graph that will be used as a baseline for the capability of each individual solar cell.

The construction process includes steps to build the solar cell measurement system (SMS), solar panels and the communications and how to integrate them together. Also included is the procedure on how to use the thermal-vacuum chamber.

The program management section will discuss the decisions made regarding the program. It will also include budgetary pitfalls and procedures as well as milestone timelines.

As program manager, the author was given an opportunity to take ownership in the project that otherwise might not have been possible. Responsible for budget, schedule and technical deliverables, the program manager had to make a plan and adjust it when necessary. Balancing the cost among travel, equipment and software expenses was necessary to complete the satellite without going over budget. Making efficient use of the personnel assets that became available was critical to completing the prototype on time. Gaining this level of management experience as a junior officer provides great benefit to career progression.

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II.   BACKGROUND

A.   HISTORY OF SPACECRAFT SOLAR CELL FAILURES

Space is a harsh environment for electronics. The corrosive nature of atomic oxygen has caused problems for satellites in low earth orbit (LEO). Solar cells can be susceptible to this atomic species that dominates from 200km to 700km in altitude. Any exposed electronics will be swiftly deteriorated, including solar cells. Solar flares can also cause rapid degradation or failure of solar cells at any orbit. By identifying which solar cells are not susceptible to destruction or rapid degradation in the space environment, the useful life of satellites powered by such solar cells can be prolonged.

One method used to protect solar cells from the effects of atomic oxygen is to use glass cover slips over each solar cell. Another method to protect solar cells is using a thin polymer layer.

Many satellites have had their useful life shortened when solar flares disrupted their solar panels. Most notable of these are Medori II, Tempo 2, GOES-7, GOES-5 and Mareks 1. Medori II was caught in a solar storm from 22 to 30 October 2003. During that storm its solar panel output permanently dropped from six kW to one kW. Tempo 2 could not withstand a solar storm and parts of its solar panel short circuited. From 22 to 24 March 1991, GOES-7 got hit by intense radiation from a solar flare that degraded the solar panels so severely it lost two to three years of its planned lifetime. On 19 October 1989, a solar flare caused a -.5A solar panel output on GOES-5. The damage to Mareks 1 solar array caused by solar activity led to satellite failure on 25 March 1991 (www.solarstorms.org/Sscope.html, accessed 06 August 2008). By identifying solar cells that are least susceptible to rapid degradation caused by solar weather, the lifetimes of many satellites could be lengthened. Expected rate of degradation is 3.75% per year for Si solar cells, 2.75% per year for GaAs solar cells and .5% per year for multijunction solar cells (Wertz, 412).

B.   PHOTOVOLTAICS

1.   History of Solar Cells

The Sun's energy has been harnessed to create electricity for many years. Solar radiation is transferred into electricity using the photovoltaic effect. Photovoltaic cells have been generating electricity since 1883 when Charles Fritts, an American inventor, built the first solar cell. It had an efficiency of one percent. The first satellite to fly with solar cells was the U.S. Navy satellite Vanguard1 in 1958, which had an efficiency of six percent. The benefit of using photovoltaic cells on spacecraft was proven, spurring new advanced solar cell research. Through years of development the efficiency of solar cells has steadily increased. By the end of the 1980s, efficiencies of seventeen percent were achieved with GaAs single junction solar cells. In 1993, the first dual junction solar cell produced an efficiency of 20 percent. Commercial triple junction solar cells reached efficiencies of 24 percent in 2000, 26 percent in 2002 and 28 percent in 2005. In 2006 Spectrolab® demonstrated a solar cell efficiency of 40.7 percent in laboratory testing (en.wikipedia.org/wiki/Solar_cell, accessed 06 August 2008).

2.   Function of Solar Cells

The photovoltaic effect begins with a photon striking the semi-conducting material. When the photon is absorbed by the material, the energy excites an electron creating an electron-hole pair. The electron and hole are then separated by the structure of the device, with the electron having a negative charge and the hole having a positive charge. A difference in electric potential is created. The electrons and holes flow in opposite directions creating a current which in sufficient amount can be converted into direct current (DC) electricity (Markvart, 6-9).

One way to increase the efficiency of solar cells is to limit the reflection of light from a cell ensuring more absorption. Two optical methods to reduce reflection are applying an anti-reflection coating and using geometry to trap light within the cell. By applying a thin layer of anti-reflection coating much more light penetrates into the solar

cell, thereby increasing the efficiency. By using a solar cell with a randomly textured top surface, reflection is reduced and it helps trap light within the cell (Markvart, 12-15).

The p-n junction is a commonly referenced silicon solar cell. It consists of three regions: an emitter, junction region and base. The emitter, or n side, and the base, or p side, absorb the majority of the light and transport the holes and electrons to the junction. An electric field develops over the junction and creates a diode that allows current to flow in one direction. Electrons can pass from the n side to the p side, and holes can pass from the p side to the n side, but not the other way around. The current created is harnessed as DC electricity (Markvart, 15-21).

Each semi-conductor material has a characteristic band-gap which enables it to absorb light most efficiently at a specific energy level, measured in electron volts (eV). A single material is limited because it can only absorb a small portion of photon energy levels from the broad solar spectrum. Energy levels outside this optimum band-gap will either pass through the material or be absorbed as heat. By utilizing multiple band-gaps, a broader energy spectrum may be absorbed, potentially increasing the efficiency. These new solar cells are referred to as Multi-Junction solar cells. Currently there are dual junction solar cells and triple junction solar cells (en.wikipedia.org/wiki/ Multijunction_photovoltaic_cell, accessed 06 August 2008).

The NPS-SCAT prototype is uses Triangular Advanced Solar Cells (TASC) derived from Spectrolab® Improved Triple Junction Solar Cells. When Spectrolab manufactures the large solar cells there is an excess amount that is cut off from the edges of the cells that are too small to be used commercially. These cells are recovered and sold to educational institutions at a discounted price. The solar cells are composed of $GaInP_2$, GaAs and Ge on a Ge substrate. They are designed to be 27 percent efficient at 25 degrees Celsius.

C. NPS SPACE SYSTEMS OPERATIONS CURRICULUM

The Space Systems Operations curriculum is a 24-month program designed to give its students a general understanding of how space systems work, knowledge of what

assets are operationally available for users as well as the tactical and strategic understanding of their employment. The students generally have four courses every quarter and spend between fourteen and eighteen hours in the classroom each week. They receive instruction from experts in the field such as astronauts, military space operators and professors of various space related disciplines. The first year of the curriculum is spent crunching numbers while the students learn orbital mechanics, launch systems, effects of the space environment, communications, optics and spacecraft design. The next year is spent applying that knowledge on design projects, operational applications and research for the thesis.

III. CONSTRUCTION PROCESS

A. SOLAR CELL MEASUREMENT SYSTEM

The SMS (Solar Cell Measurement System) is the NPS-SCAT payload. It is the system that measures the solar energy received by each individual test cell. The solar cells receive the sun's radiation and transfer it to electrical energy. Using a variable voltage input, the SMS varies the current through the solar cell, thereby enabling a measurement of the cell at the full range of current and voltage. The resulting data is stored on the satellite along with the data received from the sun sensor and the temperature sensors. The operational concept for the flight unit is that when commanded by the ground station, the satellite will transmit the data (current, voltage, sun angle and temperature) down. Once on the ground, the current-voltage data determines the efficiency of the cells and can be compared to similar sun angles and temperatures of experiment sets taken on the ground and earlier in the flight. This data will characterize the solar cells response to the space environment over time.

1. Programming

Rowley Associates® developed a program called Crossworks Compiler using the "C" programming language. The CubeSat Kit® was delivered with a generic program that enables programmers to get started on their satellites. This program allowed the user timely communication with the development board. The only problem with this program was its size. It provided code for a large number of functions that NPS-SCAT would never need. To increase understanding and reduce amount of memory required, code that was not essential was eliminated. The first test of the code was to change the blink rate of the LED on the development board. With this first confidence building step done, it was time to develop the programming code to use the various capabilities of the CubeSat Kit®, such as the communications system, the data storage system and finally to perform solar cell measurements.

### a.	Development of the SMS Programming

To program the SMS, an understanding of how the CubeSat Kit® bus interfaced with the SMS circuit was needed. The SMS circuit needs a variable voltage input and a way to measure the resulting voltage from the solar cell. The CubeSat Kit® Rev C uses a microcontroller, the MSP430 F1612, with two Digital to Analog Converters (DAC), of which only one is available. The unused DAC provides the variable voltage input. The MSP430 F1612 has eight Analog to Digital Converters (ADCs), of which some can be used to measure the output voltage of the solar cell being measured.

The first step in the SMS programming was to take the input voltage from the DAC to the ADC and to do a rough calibration of the DAC and ADC components, shown in the figure below. This program showed that these critical components were available and working. This would be the basis for the SMS program. Once this was done, integrating the radios on the development board was the next step.
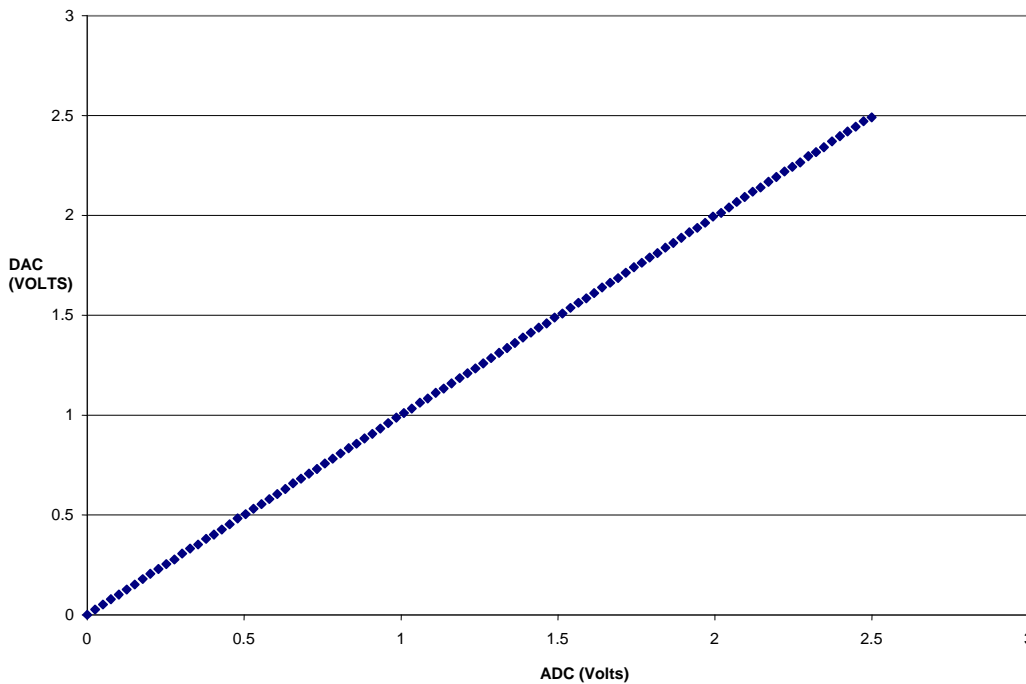
Figure 4.	DAC-ADC testing

b. *Transceiver Integration*

Early on, getting the satellite operation program to work with the radio proved frustrating. The MHX2420 radio is designed to operate with the CubeSat Kit® without any integration besides plugging it in correctly. When the radio was in the CubeSat Kit® development platform and full power transmission was used, the radio would shut off. There is a current limiting switch protecting the electronics on the development board, implemented for the lower power, previously used by the MHX2400. Since full power transmission was not needed for the prototype, the MHX2420 was set to low power to complete the experiment.

c. *Completion of the SMS Programming*

With the basis of the SMS program and the SMS breadboard complete, the next step was to apply the SMS program to the circuit using the DAC as the voltage input and the ADC to measure the output voltage from the solar cell. Once a successful IV curve was taken, the new goal became to get an average of several samples taken from the same cell. This averaged out the noise and generated a smooth IV curve and a maximum power curve both shown in Figure 5.

Solar Cell current & Power
(2008-07-01 1655 cell 13 cloudy proto-SMS assembled)
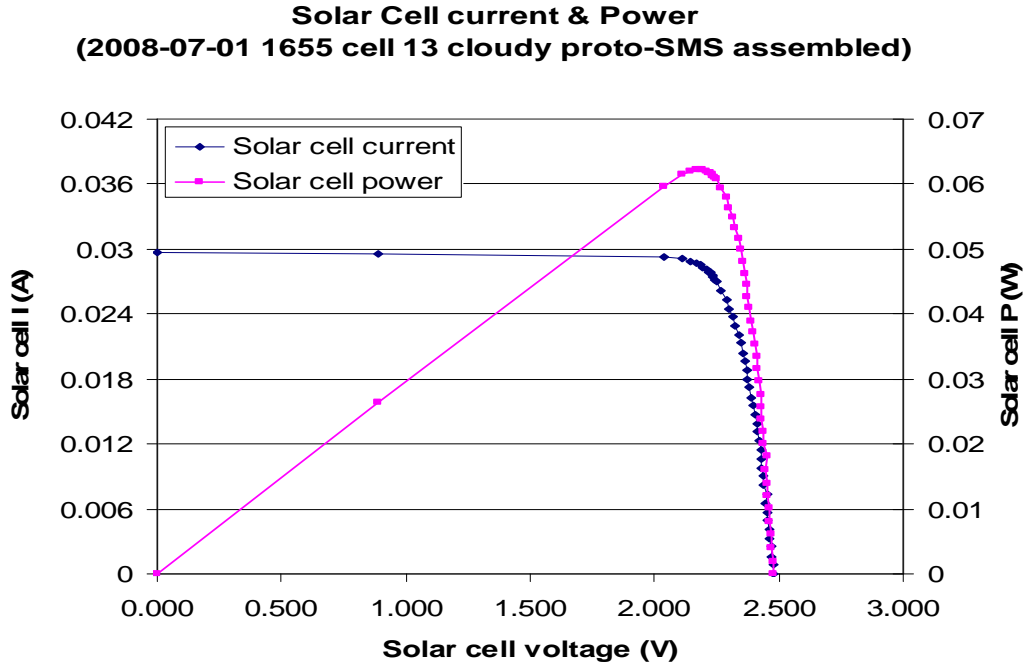
Figure 5.   Solar Cell Current and Max power

d.   *Integrating the Temperature Sensors*

The next step was to integrate the temperature sensors. The temperature of the solar cells is important to know because it affects the efficiency of the cells. The warmer the solar cell becomes, the less efficient it is (Yates, 19). The experimental solar panel was designed to integrate a total of four MAX6630 temperature sensors on both the top and bottom of the panels. The temperature sensors are surface mounted using SOT23-6 technology pictured in the figure below at a scale of 20:1. The power solar panel has one temperature sensor on each of the panels. Having sensors on both sides of the panels gives the operator a better understanding of the insulation properties of the solar panels. It also allows the operator a better estimation of the true temperature of the solar cell being tested. The MAX6630 temperature sensors are accurate to within one degree Celsius at a range from 0 Celsius to 70 Celsius. (MAX6629-MAX6632 Datasheet, 1).

18

To physically connect the temperature sensor to the solar panel, it must be soldered. The instructions to solder the temperature sensor can be found at the end of Appendix A.
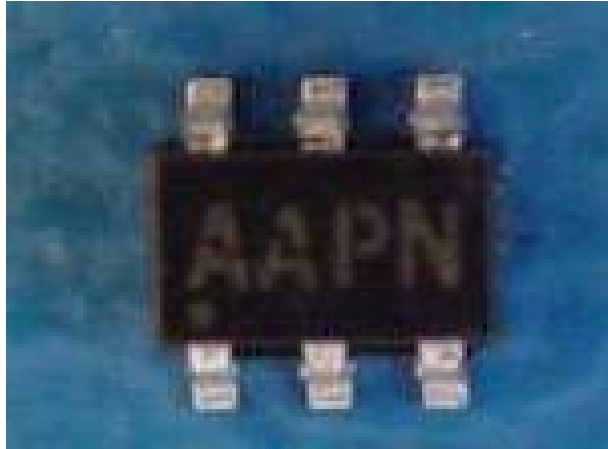
Figure 6.   SOT23-6

The temperature sensors have a three-wire/serial peripheral interface (SPI) and are in slave mode. Of the six pins on the sensor, pin one is connected to ground. Pin two is not used. Pin three is connected to 3.3V from the CubeSat Kit® bus. Pin four is the clock (sck) and is connected to CubeSat at H1, pin 21. Pin five is the chip select ($\overline{CS}$) and is connected to H1, pin 24. Pin six is the master input (SOMI-Slave Out Master In) wire and is connected to H1, pin 22.

2.   Circuitry

The NPS-SCAT SMS circuitry builds on heritage from the circuit already designed for NPSAT1 and is shown in Figure 7. Adapted for use on a CubeSat, it utilizes the 5V power supply, ground, DAC and ADC from the CubeSat Kit® bus. A 5V input from the bus supplies power to the voltage converter. An output of +/-10V from the MAX680 powers the OP97 Op Amp and the AD620 Instrument Amplifier. The DAC voltage of up to 2.5V runs to the non-inverting side of an OP97 Op Amp that controls the 2N6796 MOSFET, to keep the inverting input of the OP97 at the DAC voltage. This,

based on the value of the resistor, controls the current from the solar cell. As the DAC voltage increases, the current through the cell increases and the voltage across the solar cell decreases. The SMS ramps up the current, providing a range of current values and the corresponding range of solar cell voltages. That data is read by the ADC after it passes through the AD620 instrument amplifier. The 1N5817 Shottky diode plays an important role in protecting the solar cell from reverse bias. To prevent current from traveling the wrong way through the solar cell if there is a reverse potential on the cell, a diode was placed in parallel with the solar cell. 2.5V is the maximum output of the DAC and the assumed maximum current was 40mA. Using Ohm's law it was determined a 63Ω resister was needed to set maximum current to 40mA.

A maximum of 40mA was chosen because the solar cell short circuit current was specified as 31mA, according to the Spectrolab® TASC solar cells datasheet (www.spectrolab.com/prd/terres/tasc-main.htm, accessed 07 August 2008). Surprisingly, it was discovered that on a sunny day the solar cell could exceed the expected short circuit current. This result could be due to experimenting in cooler temperatures than the solar cells are qualified in, accompanied by the variability of the product. To enable the circuit to take measurements that include the full capabilities of the solar cell, a new resistor must be placed in the circuit. If the assumed maximum current of the solar cell is less than 50mA, using Ohm's law, the proper resistor to place in the circuit is 50Ω.
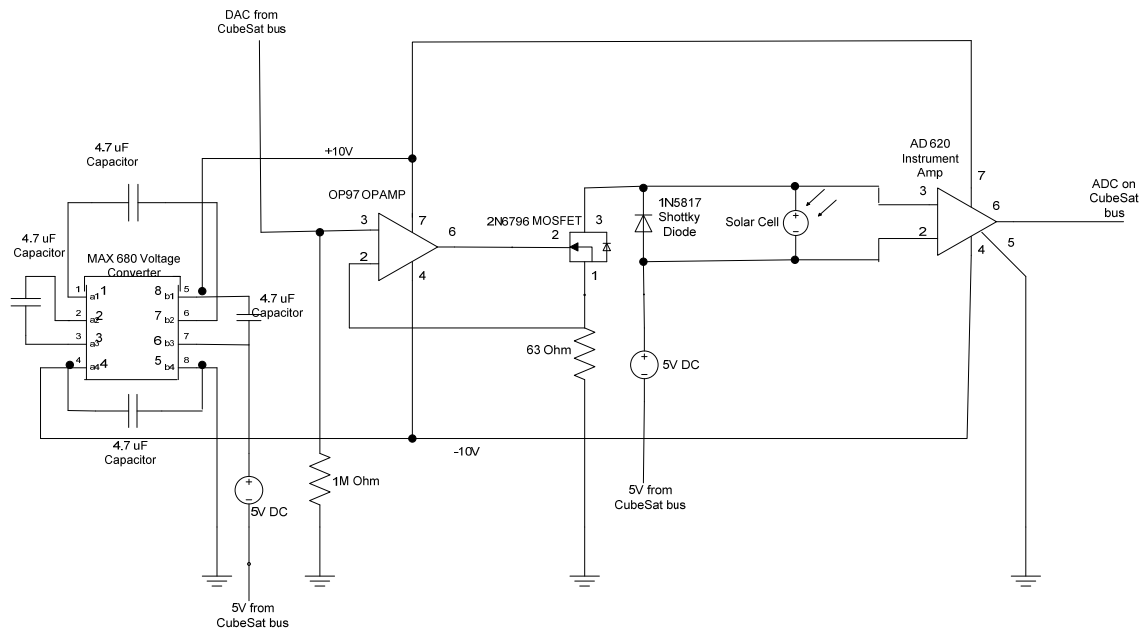
Figure 7.   SMS Circuit

The NPS-SCAT SMS circuit, shown above, was first tested on a breadboard and powered by a power supply with a multimeter measuring the output of the solar cell. The circuit is designed to test one individual solar cell at a time. By developing the circuit separate from the development board, the potential damage was limited to the components. Once the circuit was working correctly, it was connected to the CubeSat Kit® development board. The development board was providing the DAC output of 0 to 2.5V, powered the circuit with 5V, provided the ground, and its ADC was reading the solar cell input. The circuit was designed to test one solar cell at a time. Once the circuit was working and transmitting data to the ground station, the author and his thesis advisor took it outside on a sunny day and generated the first IV curves, shown in Figures 8 and 9. The noise in the data was unexpected and may have been an artifact of the experimental setup. In any case, any noise should be more fully investigated in the final configuration.
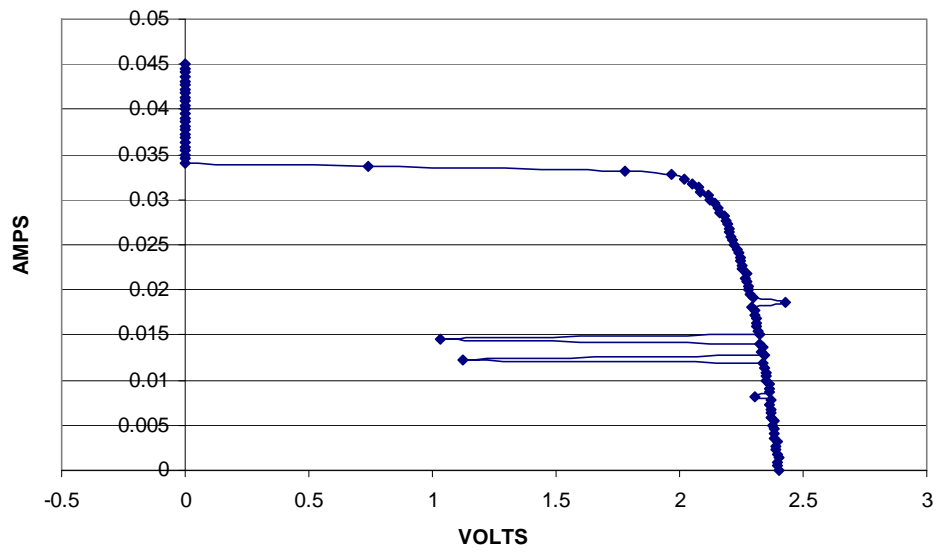
Figure 8.   First IV curve taken with NPS-SCAT SMS

Figure 9.   Thesis advisor (left) and author taking first data with the
SMS circuit attached to development board

With the circuit complete on the breadboard, the next step was to re-create the circuit on a protoboard so it could fit inside the satellite. The protoboard elegantly integrates with the CubeSat Kit® bus providing many convenient ground and power sources and connections to all of the MSP430 F1612 pins. Each component was soldered into place and the necessary connections were made on the back of the protoboard by soldering each component to its connection point using wire wrap wire.
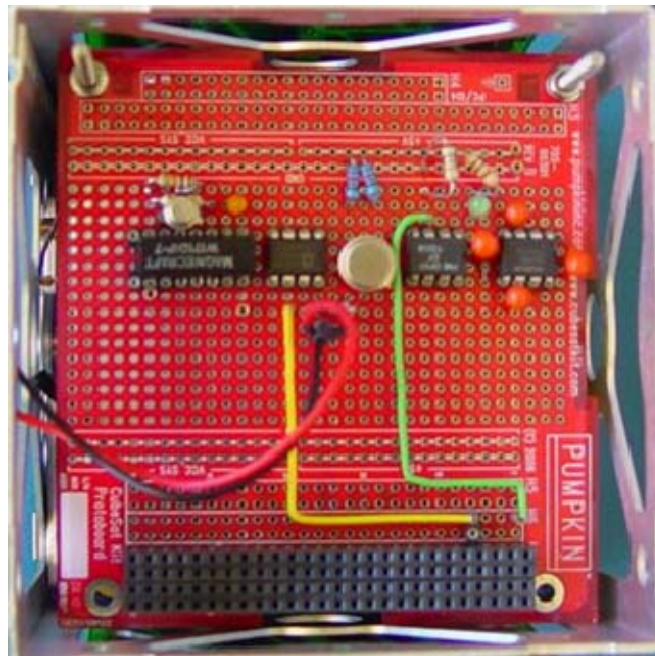
Figure 10.   SMS Protoboard

B.   SOLAR PANELS

1.   Solar Cells

The solar panels for the prototype were designed around TASC solar cells purchased from Spectrolab®. These solar cells were chosen because of their small size, low cost and high efficiency.

They are small enough to place many cells on the small CubeSat solar panels. This small size allows for placement flexibility, which is helpful to situate experimental solar cells, power solar cells, a sun sensor and temperature sensors on the experimental solar panel.

Figure 11.   TASC (Triangular Advanced Solar Cells)

Compared to larger solar cells, they are very inexpensive. A box of 100 TASC solar cells is only $250.00, enough for five solar panels. To fill five solar panels with larger cells, it would cost over $3,000. While larger solar cells cost more, requiring fewer per panel reduces complexity, making them more desirable for satellites with high energy requirements.

At beginning of life, the TASC solar cells are 27% +/- 3% efficient at 25 degrees Celsius making them some of the most efficient cells available on the market. They are Advanced Triple Junction Solar cells, which are over twice as efficient as typical silicon cells. According to the TASC solar cell datasheet, at 25 degrees Celsius each cell provides approximately 31mA at 2.5V giving 75mW. Each string of four cells provides 31mA at 10V giving 0.31W. Each panel consists of five strings of four cells in parallel, providing 0.155A at 10V giving 1.55W (www.spectrolab.com/prd/terres/tasc-main.htm, accessed 23 July 2008). Observed performance of the cells far exceeded the expected performance advertised on the data sheet, so the data sheets are conservatively written.

On a cloudy day, the solar cell achieved the expected performance of the solar cell as seen on Figure 5. On a sunny day, the current appears to have exceeded 40 mA.

2. Experimental Solar Panel

The experimental solar panel was the first solar panel designed for this project. The exact dimensions for the panel and the keep-outs were obtained from the Pumpkin® solar panel specifications sheet. The sun sensor would be placed in the center of the panel with the experimental solar cells placed around it. The goal was to optimize the number of solar cells on the face. The design called for eight test cells and the remaining twelve cells would be used exclusively for power generation. After the panel was drawn out and optimized for number of solar cells, it was submitted to Advanced Circuits® for printed circuit board production. The panel was designed to allow the operator to test the eight test cells individually. The experimental solar panel can be seen in the figure below.
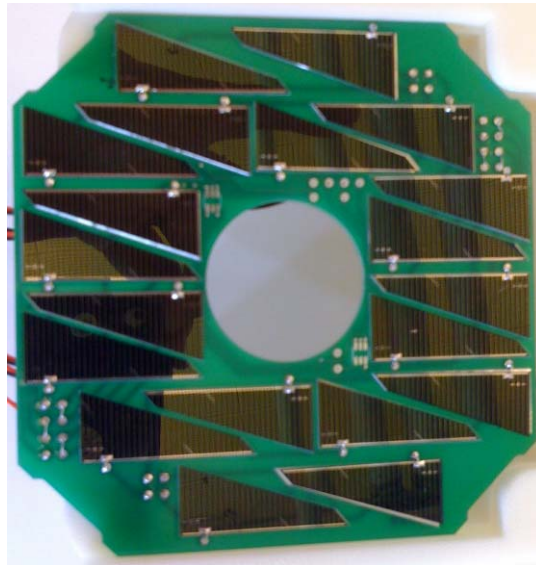
Figure 12.   Experimental Solar Panel

The experimental solar panel has 20 solar cells, four temperature sensors and a hole for the sun sensor. The top two solar cells are in series. The next row has four solar cells in series. The center eight solar cells are not in series with any other solar cell

allowing them to be tested individually. The next row has four cells in series. The last row has two solar cells in series. There are two temperature sensors on the front and two on the back. They have SOT23-6 interfaces of which five pins are used. Each temperature sensor uses a common power, ground, clock and data out connection. The fifth pin for each is connected to its own chip select connection. Temperature sensors were placed on both sides of the board to identify temperature differentials between the outside of the spacecraft and the inside of the spacecraft. There is a concern that the black surface of the temperature sensor might warm up faster than the solar cells. The figure below shows the circuit diagram for this solar panel.
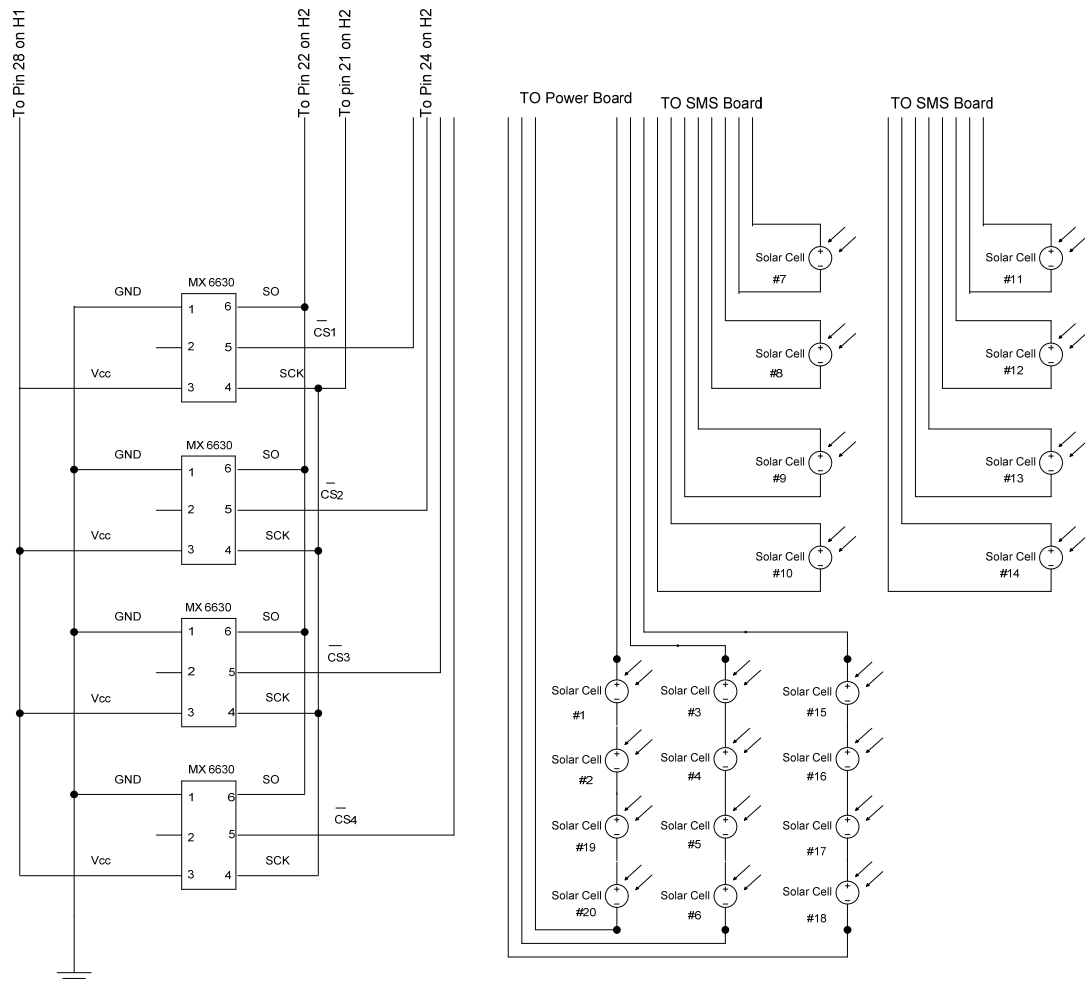
Figure 13.   Experimental Solar Board Circuit Diagram

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Having seen the solar panel layout at Stanford, NPS developed a process to produce similar panels. The cells were soldered onto the solar panels using a hot reflow plate and a heat gun. The hot plate was used to get the temperature of the solar cells close to the reflow zone, and the heat gun was used to elevate the cells above the reflow zone one cell at a time. Step by step directions on how to affix the cells, wiring and temperature sensors to the solar panels can be found in Appendix A.
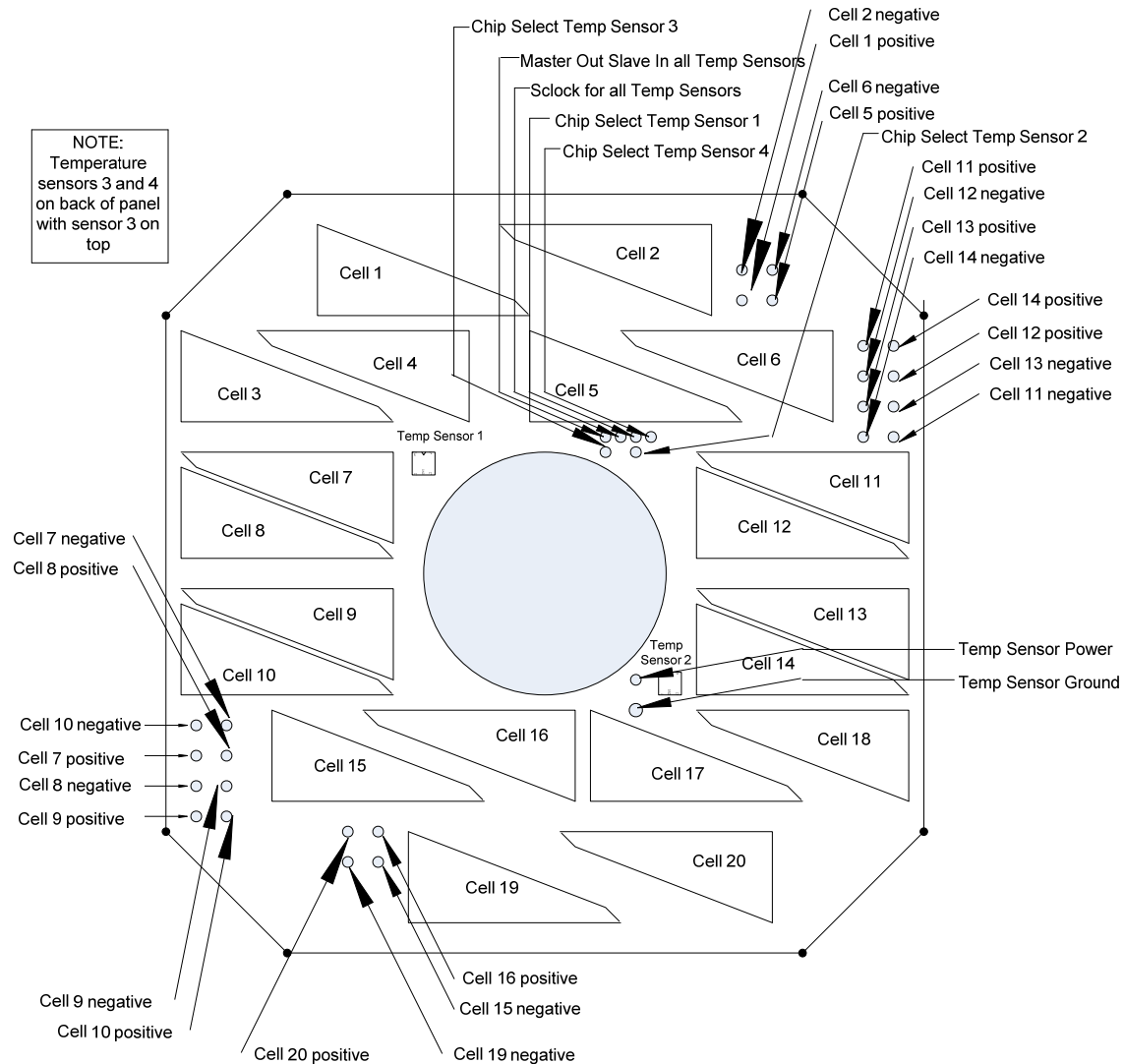
Figure 14.   Experimental Solar Panel Connections

When affixing the solar cells to the solar panel different solder paste configurations were tried in an effort to find out if the process is sensitive to the amount and the location of the solder paste. By learning the sensitivities of the process, one hopes to learn how to reliably affix the cells to the panels.

On experimental solar panels #1 and #2, many different patterns of solder paste were applied to the solar cell pads in an attempt to trap air bubbles, to cause the panel to fail. The different patterns seemed to have no effect. When the solder flows, the cell visibly gets sucked down to the pad. At this point the air is forced out through the liquid solder. <u>All the cells</u> worked in the thermal vacuum chamber in down to a pressure of $1*10^{-5}$ Torr and through a temperature range of about -30C to +70C.

The amount of solder used ranged from a pinpoint dot, to a full, thick layer. The amount of solder seemed to have little effect on the functionality of the cell, up to a point. One cell was covered in a very thick layer of solder paste, and when it flowed and solidified, it bulged out and touched both leads, shorting out the solar cell. After the excess solder was scraped away, the cell worked to specifications.

Properly heating the solar cell to flow the solder was critical to prevent damage to a solar cell. On power panel #3, the cells were not heated evenly which did not allow the solder to flow completely. This caused six of ten solar cells to bow outward, with one of them breaking. By applying the heat to the bowed cells a second time, five of the cells flattened out and adhered to the whole pad.

The bowing of the cells was a perplexing problem. It seems to occur when the solder does not completely flow across the whole cell. The solder paste pattern used on the bowed cells was a single dot of solder at each end of the cell. Presumably, the heat was not applied long enough to flow the solder across the entire pad. The solder adhered locally to each end while the solar panel pad expanded due to heating. When the solar panel pad contracted because of cooling, strain was placed on the center of the cell causing it to bow upwards. This theory assumes the coefficient of expansion due to heat

is greater for the panel than the solar cell. In order to prevent this phenomenon from happening, it is important to ensure the solder from each solar cell flows completely and evenly over the entire pad-solar cell junction.

3.   Power Solar Panel

The second solar panel designed could be used for three of the four chassis walls. The last chassis wall has additional cutouts for the antenna, remove before flight pin, USB port and power port. After the panel was drawn out and optimized for number of solar cells, it was submitted to Advanced Circuits® for printed circuit board production. The panel has five strings of four cells in parallel giving the panel about 10V with a current of 155mA at 25 degrees Celsius, assuming 31mA per string. This gives a beginning of life power of 1.55W for one face directly in the sun. There will rarely be one face directly in the sun, more likely there will be two or three faces in the sun at any moment. It is assumed the resulting power received from the sun will be roughly equivalent to one face in full sun regardless of the spacecraft orientation to the sun.

The power solar panel has 20 solar cells and two temperature sensors. Its components and connections can be seen in the figure below.
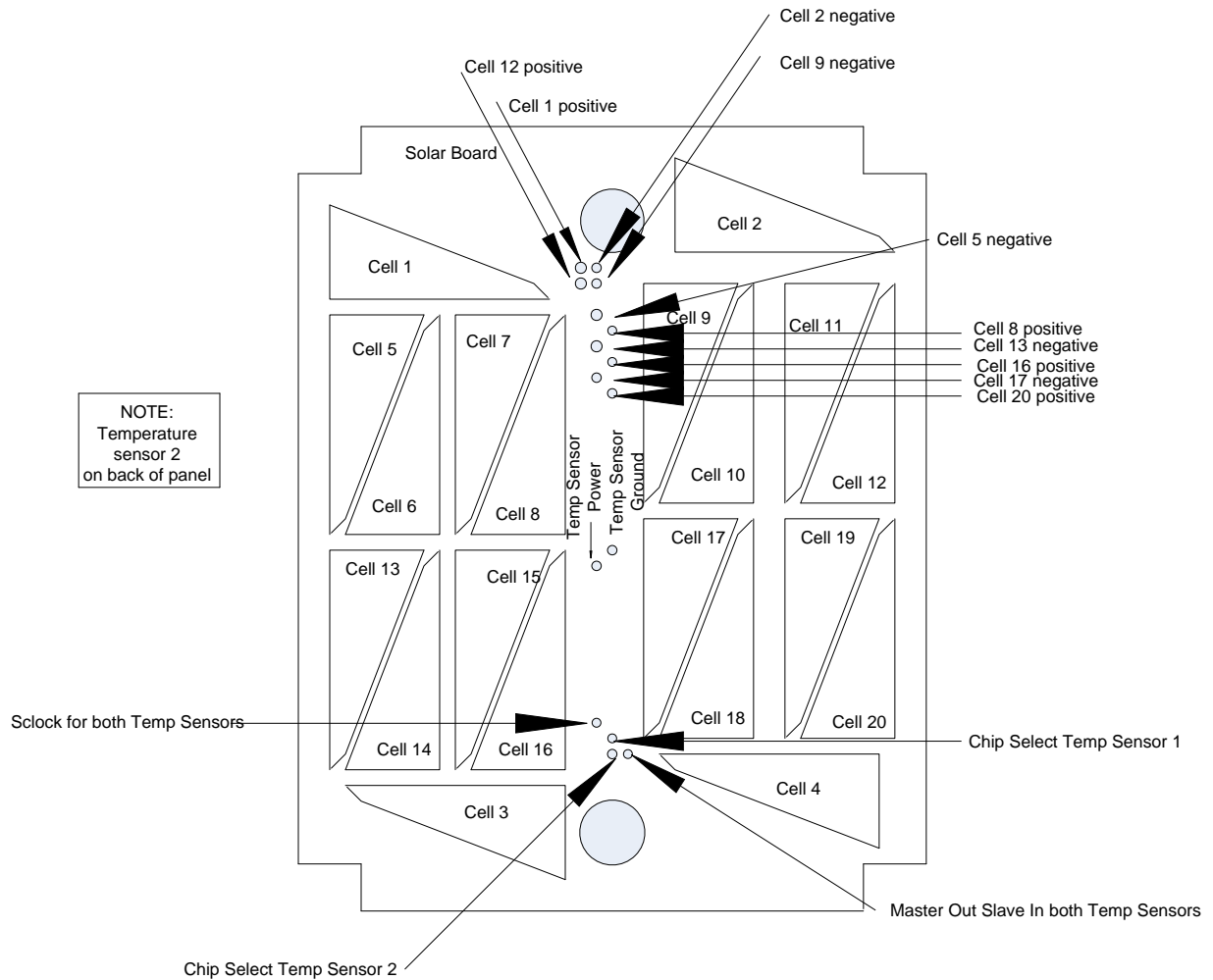
Figure 15.   Power Solar Panel Connections

The manufacturing process used to affix the components to the power solar panel can be found in the Appendix. The power solar panel can be seen in the figure below.
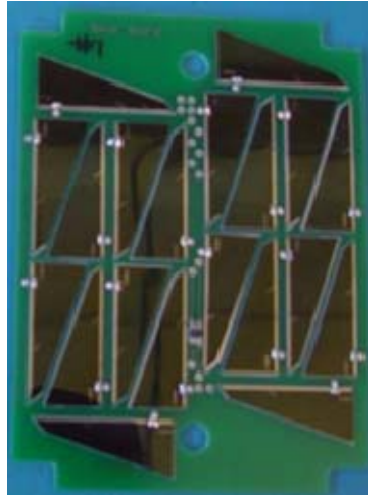
Figure 16.   Power Solar Panel

The power solar panel has 20 solar cells arranged in five strings of four. It has two temperature sensors, one in front and one in back. The figure below depicts the power solar panel diagram.
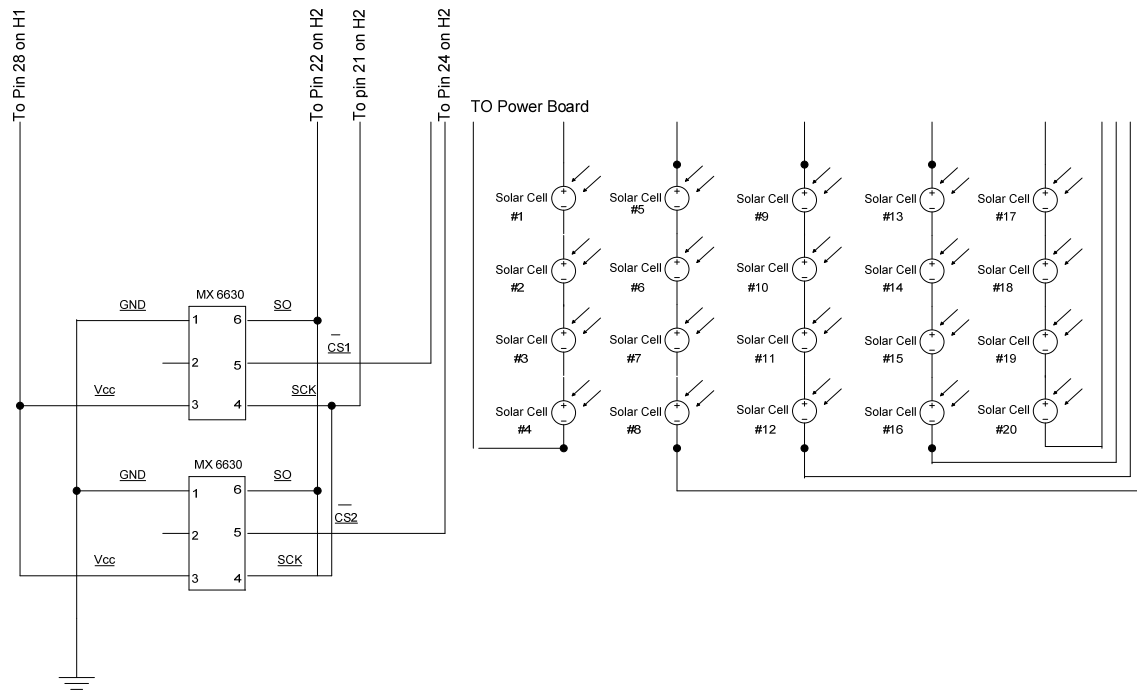
Figure 17.   Power Solar Panel Circuitry Diagram

C. POWER

The power board utilized for the prototype was the Pumpkin® linear power supply. The linear power supply was purchased because of its compatibility with the CubeSat Kit® components. It plugs right into the CubeSat Kit® bus. The limitation to the linear power supply is that it can only be charged with the USB. It cannot be used on the flight unit.

The flight unit will need to use a power board that accepts power from the solar cells. A power board has been identified for the flight unit from Clyde Space.® It is designed to work with the CubeSat Kit® bus. To make the flight unit solar panels compatible with the Clyde Space® EPS, new solar panel designs will have to be made. The solar panels designed for the prototype were not designed to meet the required Clyde Space® power board range from 3.5V to 10V and a maximum current of .5A (Clark 2). Four cells in series provide a beginning of life voltage of 10V at 25C and possibly higher at colder temperatures. Since 10V lies at the maximum of the Clyde Space® EPS specification, it is recommended future panels be built with two or three TASC solar cells per string. When developing the panels for the flight unit, care must be taken to ensure the 10V maximum is not exceeded.

D. COMMUNICATIONS

The NPS-SCAT prototype is using an MHX2420® transceiver purchased from Microhard®. The transceiver's predecessor, MHX2400® has flight heritage with GeneSat-1. To close the link, GeneSat-1 used the ten-meter dish antenna owned and operated by Stanford Research Institute (SRI). The resulting gain of the ten-meter antenna is 45dB. (Mas, 4). The three-meter antenna on top of Spanagel Hall at NPS provides 37dB of Gain. Despite the three dB increase in sensitivity from the MHX2400® to the MHX2420®, NPS-SCAT will not be able to close the link without additional gain. To close the link with the three-meter dish on the roof of Spanagel, a ten-watt bi-directional amplifier is needed. This option would require an experimental license from the FCC, since FCC section 15.247 prohibits antenna gain exceeding 36dBm (Microhard

4) within the ISM (Industrial, Scientific, Medical) radio band. The frequency used is 2.4GHz, which falls within the 2.4 to 2.5GHz ISM radio band. Another option to close the link is obtaining access to a ten-meter dish, such as the antenna at SRI. All link budget calculations were performed with an omni-directional antenna on the CubeSat. The link budget can be found in Appendix C.

To aid in the development of the communications system, a development kit was purchased that included two additional radios along with their corresponding development boards. They allowed the user to plug the radios directly into the computer serial com port and begin transmitting. The communication setup aided rapid development of communications with the radios on the development board and on the CubeSat itself. The baud rate was set to 9600.

To test out the range of the MHX2420 one radio was taken to a hill about five miles away, Jacks Peak located in Monterey. The radio successfully transmitted to the three-meter dish on the top of Spanagel Hall.

E. THERMAL VACUUM TESTING

The manufacturing process for the solar panels was unproven. Many different soldering styles were used in an attempt to produce a solar cell failure. Once the cells were affixed to the panels they were tested with a multimeter to ensure good connections. Once it was determined all the solar cells worked correctly, the experimental panels were placed in the thermal vacuum chamber and tested at extremely low pressure and at expected temperature extremes. Each solar cell was connected to a wire that was connected to a multimeter that measured the cell's distinctive resistance. A large increase in the resistance could indicate a broken connection. The chamber was brought down to $1 \bullet 10^{-5}$ Torr. The temperature was reduced to -30 degrees Celsius, and then brought up to 70 degrees Celsius. The whole time the cells were in the chamber their resistance was measured. Low pressure and low temperature induced slightly higher resistance. High temperature slightly reduced the resistance of the solar cells. Instructions on how to perform a complete test in the thermal vacuum chamber can be found in Appendix B.

The conclusion of the test was that the solar cell affixing procedure is effective.

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IV. OPERATION

A. NPS-SCAT PROTOTYPE

NPS-SCAT prototype is designed to test solar cells free of an external power supply and transmit the data to the ground station. The experimental solar panel has 20 cells total with eight capable of being tested individually. The current configuration tests only one cell until the leads are manually changed. When the test is complete the data is stored and transmitted to the ground station. The ground station for the prototype is a Dell computer attached to an MHX2420 radio that matches the transceiver in the prototype.

1. Requirements Overview

At the outset of the NPS-SCAT project, the following requirements were laid out.

Mission Requirements

1. Build a solar cell testing CubeSat prototype.

2. Reference orbit to be simulated by STK.

    a. Low earth orbit-prefer a minimum of a two year orbital lifetime with a maximum life of 25 years after mission completion

    b. Slowly tumbling satellite

    c. Power budget

3. Meet all safety requirements delineated by all potential launch facilities and applicable DoD instructions for the flight unit.

Experiment

4. NPS-SCAT needs the ability to accurately and precisely measure solar cell current and voltage to within the following tolerances.

    a. Measure solar cell voltage to within +/-10mV

b.   Measure solar cell voltage range from 0 to 2.7V

c.   Measure solar cell current to within +/-0.1mA

d.   Measure solar cell current range from 0 to 40mA

e.   Measure 100 data points per curve focusing on the max power point

5.   NPS-SCAT must be able to be tested in NPS facilities' solar simulator or in direct sunlight with no external power source.

6.   NPS-SCAT must have the ability to determine relative sun vector to the experiment cells within +/- .5 deg.

7.   Standard data output of test will be: Time stamp, sun angles, temperature, experiment cell voltages and currents.

Experimental Solar Panel

8.   The experimental solar panel must fit the cover plate area for the 1U CubeSat with clips.

9.   The experimental solar panel must have a 30mm diameter cutout for the solar sensor.

10.   The experimental solar panel must have ability to measure temperature of panel surface.

Spacecraft structure

11.   The NPS-SCAT prototype will use a standard (1U) CubeSat frame.

12.   The spacecraft structure will minimize deploying or moving mechanisms.

COMMS

13.   Satellite will have command and data handling to communicate with the ground station.

14.   A ground station must be established to communicate with the satellite.

15.   The ground station must be able to send commands and data to the satellite.

16.   The ground station must be able to receive data from the satellite.

Electrical Power System

18.   The flight unit must be able to transfer solar power from the power cells to charge the battery and power the experiment.

19.   The flight unit must be able to power core systems continuously, the communication transmitter and experiment hardware as required to collect the requisite data.

2.   Mass Budget

It is important to pay close attention to the mass of the CubeSat. The CubeSat standard specifies a maximum mass of one kilogram. The mass budget below is based on a technique that uses an average amount of solder.

Component	Mass
Structure with FM430 flight board	210g
Six solar panels with wiring	270g
Sun Sensor with mounting platform	70g
Radio	50g
Clyde Space® EPS	150g
SMS Protoboard	80g
Total	830g
20% Margin	170g
Total (max)	1000g

Table 2.   Mass Budget

With an estimated mass of 913g the satellite is within its weight requirements, but with the addition of an antenna, its cabling and any thermal protection, it will be much closer to the one kg limit.

3. Power Budget

The power budget was not developed for the NPS-SCAT prototype. The flight unit will need a thorough power budget. The power budget must include observed power usage, and peak power usage from all components along with their power cycle. The power usage is graphically depicted with power generated by the solar cells along with time in sun and time in eclipse. The depth of discharge of the batteries will be determined by the length of time in eclipse and the power usage.

B. NPS-SCAT FLIGHT UNIT

The flight unit will be able to test all eight test cells sequentially with some the cells providing power to the satellite when they are not being tested. Once the first four cells are tested, they will be switched to provide power, and the four test cells that were providing power will be tested individually in sequence. When the satellite is not testing the experimental solar cells, they are on-line for power generation. The sun angle and the temperature of the solar panel will be recorded along with the solar cell data. The data will be stored on-board until a command link with the NPS ground station is established and then the data will be transmitted to the ground station.

1. Data Budget

The satellite will downlink housekeeping data and experimental data. The housekeeping data will include state of battery charge, and temperatures from the two of the power panels. Experimental data will include current and voltage data from each experimental solar cell, temperature readings for beginning and end, sun angle for beginning and end and a timestamp. The housekeeping data can be transferred in three bytes. If running one experiment the experiment data can be transferred in less than a kilobyte.

	Sun Angle	Temperature	Time	IV Data	Total
# bytes 1 Use	16	4	3	100	123
# bytes 1 Exp	32	8	3	800	843
# bytes 10 Exp	320	80	30	8000	8430
# bytes 400 Exp	12800	3200	1200	320000	337200

Table 3.   Data Budget

The satellite should have three to four passes a day over the ground station, the longest of which is five minutes or 300 seconds. Utilizing only the long pass each day allows for 360 kilobytes for downlink.   With no compression this downlink enables over 400 experiments per day.   Utilizing 50% compression, the number of experiments transferable in the downlink is over 800.

This capability far exceeds the mission requirements of the satellite, which is looking to show the long term effects of the space environment on the solar cells. The mission will require one dataset a week for two years. The satellite will downlink once per day giving the operator seven datasets to choose from. Since the satellite is not taking many datasets, there is not a requirement for a large quantity of data storage.

2.   **Orbit**

The satellite will most likely operate in a low earth orbit (LEO) between 400 and 700 km. The orbit may depend on the solar cells being tested and the manufacturer. The manufacturer might want to have them tested in the Van Allen radiation belt.   The radiation belts are a torus of high energy particles surrounding earth extending from 700 to 10,000 km and from 20,000 to 60,000 km that could damage solar cells (en.wikipedia.org/wiki/Van_Allen_radiation_belt, accessed 03 Aug 2008).   The lower belt would be the logical choice for the test because it is more cost effective and the radiation is more concentrated there. The difficulty with higher orbits like the Van Allen belt, is the de-orbit requirement. Even at the lower end of the radiation belt, 700 km, it could take close to a hundred years to de-orbit naturally, and it would take a delta V of 182.8m/s for a controlled de-orbit (Wertz 157). Since NPS-SCAT is not designed to have

any propulsion capabilities, a higher orbit would cause it to remain in space and be a potential hazard to other spacecraft for many years after its expected lifetime.

3. Tumble Rate

Since NPS-SCAT is not designed to have any propulsion or attitude control, it will be a tumbling satellite. As long as the rotation rate does not exceed three degrees per second, lack of attitude control does not significantly impact the mission. The satellite will not need to take continuous measurements. Periodic measurements that correspond to the time when the experimental face is in the sun will be sufficient.

The expected tumble rate of the satellite is approximately one revolution every 30 minutes. This estimation will be affected by the antenna chosen for the satellite. A long antenna will have a stabilizing effect, slowly reducing the tumble rate as the satellite orbits the earth. A patch antenna will have little to no effect on the tumble rate. A variety of tumble rates have been observed on CubeSats. While the rates were commonly significantly less than one rotation per minute, one CubeSat, CP3 had an estimated starting rotation of one rotation per minute. The excess rotation was believed to be caused by the antenna getting caught on the edge of the P-POD and creating a torque as it exited. The satellite eventually slowed to an estimated one revolution every 30 minutes. Damping of the rotation speed could be due to mechanical flexing of the antenna and also due to any eddy currents set up in the electrical traces on the satellite as it travels through the earth's magnetic field. Another Cal Poly CubeSat, CP4 had a tumble rate of less than one revolution every 30 minutes.

NPS-SCAT will only take measurements when the sun angle is less than 60 degrees. The sun sensor will take a measurement, if the measurement is less than 60 degrees, the SMS will record the data for a solar cell IV curve, and the sun sensor will take another measurement. The two sun sensor measurements will be recorded along with the temperature and the SMS data. Measurements will be taken in this manner until the memory is full or the spacecraft is otherwise instructed by the ground station. The time required to take the data for a complete IV curve is less than a second. With a

rotation rate of six degrees per minute, one second translates to .1 degree. A difference of less than one degree should not affect the data to a great extent.

Acceptable tumbling rates are less than half a rotation per minute or three degrees per second. Anything more than that might cause deformation of the IV curve. In a case where excess rotation is experienced, there are probably algorithms that can be developed for use at the ground station to normalize the IV curve with the use of the two sun sensor readings.

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V. PROGRAM MANAGEMENT

The program management portion of the thesis is designed to document the author's experience managing a technical project. As program manager, the author was given a budget, a schedule and a technical goal to accomplish. In this case, the goal was to build the NPS-SCAT prototype. The program manager was given support from his thesis advisor as well as support from several faculty members and students that signed up for directed studies.

A. GENERAL DESIGN

To buy the parts needed to build NPS-SCAT, a rough design of the satellite was required. It was decided that the satellite would be a 1U CubeSat using COTS components for the structure, C&DH and Power, leaving only the payload and solar panel design for NPS manufacturing.

1. Structure

The structure would be composed of a skeletonized 1U CubeSat received from Pumpkin® as part of the CubeSat Kit®. The structure is made from a light-weight and high-strength material, aluminum 5052-H32 (www.cubesatkit.com/content/faq.html, accessed 25 July 2008).

2. C&DH

The FM430 flight module is the C&DH board for the CubeSat Kit®. Besides being compatible with all the components of the CubeSat Kit®, it provides a low power consumption computing capability (www.cubesatkit.com/docs/datasheet/DS_CSK_FM430_710-00252-C.pdf, accessed 25 July 2008). The FM430 has a CubeSat Kit® bus that has the same size footprint as the PC104 standard. It is not directly compatible with the CubeSat Kit® bus, but it can be transferred to the CubeSat Kit® bus via Pumpkin®

protoboards (www.cubesatkit.com/docs/datasheet/DS_CSK_Protoboard_711-00303-B.pdf, accessed 25 July 2008), or user-designed boards.

Although the MHX2400 was ordered, the MHX 2420 radio was delivered due to its ready availability and its compatibility with the CubeSat Kit®.

3. Power

The initial design used a power board from Clyde Space®. It is an ideal candidate because it is compatible with the CubeSat Kit® bus and is capable of being powered by the CubeSat solar panels at between 3.5V and 10V. (www.clyde-space.com/1U%20CubeSat%20Power%20Datasheet.pdf, accessed 25 July). The Clyde Space® power board took five months for delivery. While that board was being developed, a linear power supply was purchased from Pumpkin.® It was more easily compatible with the CubeSat Kit® bus, and it could be electrically charged with the USB port on the CubeSat. The project manager decided to use the Pumpkin® linear power supply for the prototype, delaying the integration of the Clyde Space® power board to later.

In the beginning, it was uncertain whether or not experimental solar cells would be acquired for the prototype. In the mean time, TASC solar cells were purchased from Spectrolab® to be used as a minimum on the power solar panels. In the end, TASC solar cells were used on the power solar panels as well as the experimental solar panels. Although solar panels can be purchased from Clyde Space,® they are expensive, costing 6,000 British Pounds, or about $12,000 for five flight panels with 24 TASC solar cells on each (Clark, 9).

4. Software

It was known that software would be needed to program the CubeSat microcontroller. The Crossworks Compiler was chosen because it was recommended by Pumpkin® for use with the CubeSat Kit®. Four educational licenses were purchased from

Rowley Associates for $329.00 each. Four copies of Crossworks were needed; two for use in the CubeSat lab and two copies for the SSAG staff.

5. Solar Cell Measurement System

When the project began, there was discussion about whether to use a scaled down version of the NPSAT1 SMS or to develop a new SMS tailored to fit a CubeSat. The advantage of developing a new SMS would be the flexibility to test the cells in a different configuration. The disadvantage would be longer development time, and a duplication of effort. The advantage of using a scaled down version of the NPSAT1 SMS, is a much shorter development time, while the disadvantage is the loss of flexibility. The decision to adapt the NPSAT1 SMS to fit the CubeSat was the best choice. Faculty members were subject matter experts with specific component knowledge that saved countless hours of development and ensured the ultimate goal was possible.

B. BUDGET

The NPS-SCAT prototype was funded for $48,000 in FY08 and the flight unit is authorized for $95,000 in FY09. There is an interest in the reduced complexity, cost and timeline that CubeSat provides. The prototype funding is explicitly available through the end of fiscal year 2008 (FY08) or 30 September 2008. Further restricting how the funds are spent is the NPS comptroller. The comptroller requires all reimbursable funded miscellaneous documents to be completed by 19 September, to alleviate pressure on the office at the end of the fiscal year.

As is customary for sponsored research, the project pays for the use of the facilities and the procurement staff through indirect charges, 31.59% for FY08, or $11,523.06 of the $48,000.00. Subtracting the indirect cost leaves $36,476.94 for actual expenditures associated with NPS-SCAT.

Initially the budget was split between travel, equipment and supplies less than $15,000, equipment and supplies greater than $15,000, software and support and miscellaneous. It was estimated that $7,000 would be used for travel, no allotment for

equipment and supplies greater than $15,000, $25,000 for equipment and supplies less than $15,000, $3,476.94 for software and support with $1,000 remaining for miscellaneous costs. In the end, the equipment and supplies costs remained very close to the estimates. The biggest difference in cost stemmed from the large student involvement that drove up the travel budget, balanced by the reduced cost of software and support. The final costs were $8,585.98 for travel, $25,551.47 for equipment and supplies, $1316.00 for software and support with $1023.49 remaining for miscellaneous costs. See table and figure below for details.

Expense	Proposed	Executed
Faculty Labor	0.00	0.00
Travel	7000.00	8585.98
Equipment and Supplies under 15K	25000.00	25551.47
Equipment and Supplies over 15K	0.00	0.00
Software and Support	3375.00	1316.00
Miscellaneous	1000.00	1023.49
Indirect costs	11625.00	11523.06
Total	48000.00	48000.00

Table 4.   Budget
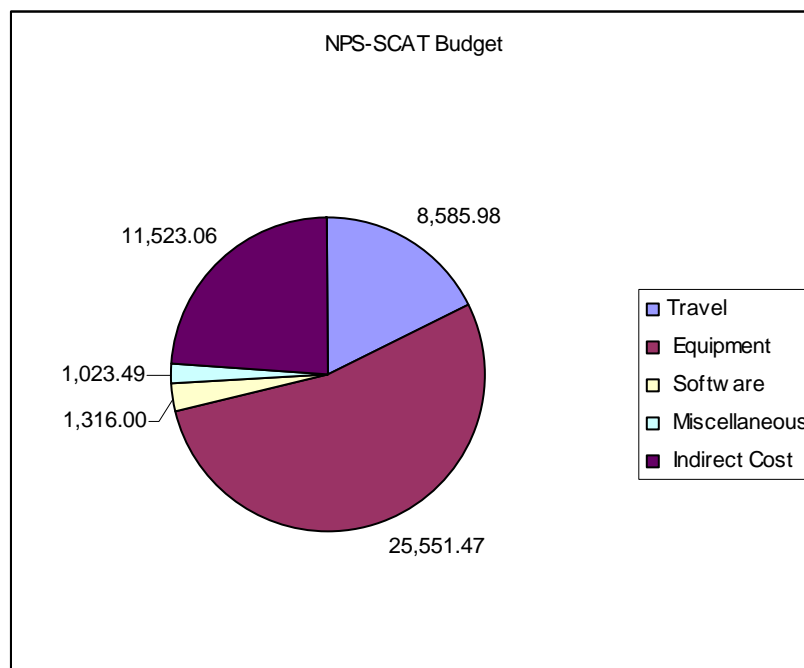
Figure 18.   Budget Allocation

It is important to accurately estimate costs the project will incur. However, a development effort by its very nature must have some uncertainty in cost estimation. For larger expenses, the estimates are usually easier, because there are fewer of them and their prices will not vary much. Small components and tools can be harder because there is price and product variability.

Estimating travel costs also includes some uncertainty because it is hard to predict, a year ahead of time, how many people are going to travel on any particular trip. NPS-SCAT welcomed the support the additional students brought and adjusted the budget allocation to pay for the travel costs. Several websites exist to help estimate travel costs. Per Diem rates can be found at http://perdiem.hqda.pentagon.mil/perdiem/rateinfo.html. Privately Owned Conveyance (POC) can be found at http://perdiem.hqda.pentagon.mil/perdiem/faqpovpast.html. Flight costs can be estimated at http://apps.fas.gsa.gov/citypairs/search/. Estimating hotels, rental cars and parking can be harder, but decent estimations can be made based on the location.

Purchasing miscellaneous equipment and supplies must be estimated as well. The purchase process begins with research. Research must be conducted to determine what components will be needed to accomplish the mission. The required components can be found on the internet or through a catalog. The program manager was urged to use GSA www.gsaadvantage.gov for all purchases, but it was not as convenient or as inexpensive as purchasing from the companies online. It is easier to find the desired components from online companies because they have illustrations of their products and greater selection.

C.   SCHEDULE

The schedule for the NPS-SCAT prototype was driven by fiscal year funding and coincidental student graduation. Funding for FY08 ends on 30 September 2008. Graduation for Space Systems Operations students typically also occurs at the end of September. So the natural end of the program ends concurrently with the funding and the graduation of the program manager.

The NPS-SCAT flight unit project is scheduled to begin in FY09 and end after mission completion. September 2009 marks the end of the funding for production of the flight unit. It is expected that a launch will be provided by the Space Test Program (STP). To this end, the NPS-SCAT project was briefed to the Space Experiment Review Board (SERB). The SERB reviews government satellites and experiments and ranks them in order of military relevance, technology development, complimentary experiments and similar experiments. Once the SERB has ranked a program, it will be available to be offered a ride into space. Once in space, operating costs should be covered by the Space Systems Academic Group through officer students.

When planning a program, it is important to produce a timeline with the expected duration of each individual task of the project. This program was managed with the help of Microsoft Project. The NPS-SCAT Microsoft Project sheet can be found in Table 2. Using estimates of how long each task would take and breaking them up into subtasks allows a manager to better estimate the completion time of the project. When estimating how long a particular task will take, first evaluate the task. If the task is particularly innovative, triple the original estimate. If it is a mundane task that has been completed many times before, double the original estimate. Normally, engineers are optimistic, and will fall behind. This extra cushion will help protect the program manager as well as provide a more accurate estimate. If the engineer manages to complete the task ahead of time, the extra time will likely be needed for another task that runs over schedule.

ID	Task Name	Start	Finish	May 1		July 1	
				4/20	5/18	6/15	7/13
1	**Satellite**	**Tue 9/18/07**	**Fri 8/29/08**				
2	**Preliminary Design Review**	Tue 9/18/07	Tue 9/18/07				
3	**Initial Procurement**	**Tue 10/23/07**	**Tue 4/8/08**				
12	**Communications**	**Fri 1/18/08**	**Tue 5/20/08**				
21	**Power**	**Thu 1/17/08**	**Mon 6/16/08**				
22	Array R&D	Thu 1/17/08	Thu 3/20/08				
23	**Power panels**	**Thu 1/17/08**	**Mon 6/16/08**				
34	**Experiment panel**	**Tue 3/18/08**	**Mon 4/28/08**				
35	Pick out Experiment c	Tue 3/18/08	Tue 3/18/08				
36	Design panel	Thu 3/20/08	Thu 3/27/08				
37	Experiment Panel Pro	Fri 3/28/08	Mon 4/7/08				
38	Experiemental Panel	Tue 4/8/08	Mon 4/21/08				
39	Experimental panel te	Tue 4/22/08	Mon 4/28/08				
40	**SMS**	**Wed 3/12/08**	**Fri 8/22/08**				
41	SMS design	Wed 3/12/08	Tue 4/8/08				
42	SMS Design Review	Wed 4/9/08	Mon 4/28/08				
43	Perf board mock up	Tue 4/29/08	Fri 5/2/08				
44	Protoboard mock up	Mon 5/5/08	Fri 5/9/08				
45	Programming SMS	Mon 5/12/08	Fri 5/30/08				
46	SMS and Dev Board integ	Mon 6/2/08	Fri 6/13/08				
47	**Integrate Sun Sensor int**	**Mon 5/12/08**	**Tue 6/10/08**				
48	Program to integrate	Mon 6/2/08	Tue 6/10/08				
49	Design and build Sun	Mon 5/12/08	Wed 5/14/08				
50	Integrate Temperature ser	Mon 5/12/08	Mon 5/19/08				
51	PC Board layout and proc	Tue 5/20/08	Mon 6/9/08				
52	Sun Sensor Testing	Fri 8/1/08	Fri 8/8/08				
53	SMS Satellite Testing	Mon 8/11/08	Fri 8/22/08				
54	**Preliminary Design review**	**Fri 4/4/08**	**Fri 4/4/08**				
55	**Critical Design Review**	**Thu 5/1/08**	**Tue 6/17/08**				
59	**Satellite Integration**	**Fri 8/22/08**	**Wed 8/27/08**				
60	Final Fit Check	Fri 8/22/08	Fri 8/22/08				
61	Comms check	Fri 8/22/08	Fri 8/22/08				
62	Solar Panels check	Fri 8/22/08	Fri 8/22/08				
63	Power Check	Fri 8/22/08	Fri 8/22/08				
64	Satellite Assembly	Mon 8/25/08	Mon 8/25/08				
65	CubeSat Test	Mon 8/25/08	Wed 8/27/08				
66	Final Project Report	Fri 8/29/08	Fri 8/29/08				
67	**Ground Station**	**Thu 1/17/08**	**Thu 3/27/08**				
71	**Mission**	**Thu 1/17/08**	**Wed 3/26/08**				

Table 5.   Schedule

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VI. CONCLUSION

A. PROOF OF CONCEPT

CubeSat has proved to be a great platform for hands-on student education and shows great promise for performing small experiments in space and focused research objectives of national interest. The essential but non-payload related portions of the satellite take up a small amount of time to integrate. This allows satellite engineers to focus on the important part: the payload. The non-payload portions also take a proportionally small portion of the satellite of approximately 45% of the spacecraft volume. With most of the satellite dedicated to the payload, CubeSats have a lot to offer. The prototype created in conjunction with this thesis will provide guidance for many CubeSats to be built at NPS.

B. ANALYSIS

While a CubeSat is much less complex and quicker to build than larger satellites, there is still some complexity in interfacing the components and particularly the payload. By using the CubeSat Kit® components for the majority of the satellite, the complexity was greatly diminished. Nonetheless, there is still a great deal of work required to understand the CubeSat Kit®, the components of the payload, and how they integrate with one another.

When deciding what components to use, one should take special interest in the interface options. Many times the majority of the work integrating new components is adapting the interface to fit the satellite C&DH system. This can be frustrating if there was an option with a more seamless interface that could have been chosen initially. For example, the Sun Sensor might have been easier to integrate if the CubeSat Kit® had been well understood.

Special attention must be paid to the tolerances of components and ensuring the margins are taken into account. For example, the solar panels designed for this project

are at the upper limit of the voltage tolerance of the Clyde Space® EPS, bearing little margin for safety. Therefore, these solar panels should not be used with the flight unit.

C.   FUTURE WORK FOR NPS-SCAT

1.   Experimental Solar Cells

The prototype was a proof of concept for testing solar cells, and it used TASC solar cells to this end. The flight article will test experimental solar cells on orbit, which requires finding a sponsor who needs to qualify solar cells on orbit. The required orbit may be determined by the solar cells used. The manufacturer may want the test conducted in low earth orbit to determine the effects of atomic oxygen. Since the CubeSat comes in a 1U, 2U or a 3U configuration, the size of the NPS-SCAT could be determined by the size and the number of the solar cells to be tested.

2.   Power Solar Cells

The flight article will require solar cells that are shielded from the space environment. This may be achieved by purchasing solar cells that have a thin glass covering or developing a procedure to coat solar cells. Finding space rated solar cells in the size needed may prove the simplest solution. This would maximize the solar collection area and may reduce the amount of work involved in integrating the solar cell into the power system. The trade-off is that processing TASC solar cells is fairly well understood now, but some work would have to be done to understand how best to affix large area solar cells to the panels.

3.   Solar Panels

If the flight article uses the Clyde Space® EPS the solar cell string output must fit within its minimum tolerances for voltage and current. The voltage range is from 3.5V to10V and the maximum current is .5A. The maximum voltage was reached with a string

of four TASC solar cells at AM1 (one atmosphere worth of filtration). The design must account for the increase in efficiency in AM0 and the variable, but sometimes cooler temperatures of space.

4. Sun Sensor Integration

To know the efficiency the solar cells are achieving, the angle of the sun must be known. By integrating the SS411 sun sensor, the sun angle can be known to within +/-.1 degrees of accuracy, which meets the requirement of determining sun angle to within +/- .5 degrees. It has an SPI / Nano-Satellite Protocol (NSP) interface that must convert into a Universal Asynchronous Receiver/Transmitter (UART) interface. It has nine pins that should be connected using a subminiature DB9 connector, ITT part #0745-738S, as suggested in the table below.

Pin	Purpose	Description	CubeSat Kit Pin Connect	DB9 Wire Color
1	Ground		GND H2:29-32	Black
2	I/O4 SS	Slave Sel	H1:16	Brown
3	I/O2 MISO	Master In	H1:22	Red
4	Ground		GND H2:29-32	Orange
5	Drain/Reset		N/A	Yellow
6	Power in	Vcc	H2:27,28	Green
7	I/O3 MOSI	Master Out	H1:23	Blue
8	I/O1 SCK	Clock	H1:21	Violet
9	I/O5 NC		N/A	Grey

Table 6.   Sun Sensor Pinout

5. Size of the Spacecraft

It may prove beneficial to use a 2U spacecraft to test the experimental cells. The added height would allow the experiment to be conducted on up to five CubeSat faces. From a structural perspective, the limiting factor for a 1U is the size of the sun sensor. It is nearly two cm tall with a base of 3.7cm by 3.4cm, which takes up a large portion of the CubeSat. By doubling the size of NPS-SCAT you could place a sun sensor on all four long sides and the top, thereby, increasing the testable area by 800 percent. The extra

volume could also allow for attitude control. However, from a budgeting perspective, the cost of five Sinclair Sun Sensors at $10,000.00 each becomes prohibitive.

6.   Antenna

An antenna must be designed that will fit within the P-POD. A tape measure antenna that lays flat along the satellite might be one option. It would be connected through the antenna port and is fastened on the other end by a thread. Upon deployment, a one-time heating filament will burn the thread and allow the antenna's natural rigidity to straighten it out perpendicular to the satellite. This antenna should extend a half wavelength beyond the edge of the satellite, which is 6.15 cm for a 2.4GHz radio frequency. Testing will be required to verify radiation patterns.

D.   FUTURE WORK FOR CUBESATS

1.   Attitude Control

Spacecraft are dependent on attitude control for many different functions. Any spacecraft with imagery systems, directed communications, maneuvering, station keeping and a variety of experiments will need an attitude control system. An attitude control system needs the output of an attitude determination system. That could be achieved with some combination of star trackers, sun sensors, magnetometers and rate sensors. Then the attitude control system needs to be able to orient the satellite. This can be done with reaction wheels, a Gyroscope, magnetorquers and even propellant.

Pumpkin® has developed an attitude determination and control system that will take the majority of 1U of space. It is unproven in space and has a price tag of $55,000, but it could be a solution for developers who do not have time to build one or for those who are willing to pay for the convenience (www.pumpkininc.com/content/doc/forms/pricelist.pdf, accessed 24 July 2008).

2. Propulsion

CubeSats have found their niche by encouraging space education and training while enabling small experiments in space. To evolve to the next generation, CubeSats will need propulsion. To take on more serious roles in space, CubeSats will need to be able to maneuver, de-orbit, and station-keep. This will allow spacecraft engineers to take advantage of the reduced cost and complexity of CubeSats while applying them to more complex missions. TISARP (Tiny Spacecraft Assembly, Reconfiguration and Proxy-ops), mentioned earlier, is being developed to provide this needed step in CubeSat engineering. It seems that a novel opportunity presents itself to anyone who can offer micro-propulsion systems specifically for CubeSat.

3. Communications

The CubeSat concept is built around COTS components to enable rapid development. To this end, a low power communications suite with a high data rate is needed that interfaces with the CudeSat Kit® and does not require special licensing to have the gain required to close the link with a LEO spacecraft. The MHX 2420 falls within the ISM radio band at 2.4GHz, requiring an experimental license to exceed the 36dB limit set by the FCC to protect other ISM operators at that frequency. To close the link with a CubeSat fitted with the MHX 2420 a gain of 45 dB is required.

In the future, CubeSats will be employed for more complex missions and experiments, requiring a higher data rate than is offered by the MHX 2420. The next generation radio must offer developers a platform to this end.

4. Deployable Structures

Following the COTS theme, deployable structures, such as antennas and solar arrays should be made available to CubeSat developers. With no COTS options, CubeSat developers have been creating deploying antennas and solar panels. Dependable COTS deployable structures would save developers many hours of creating mechanisms and deployment schemes.

E.   OVERALL SUMMARY

In conclusion, creating the NPS-SCAT prototype has proven the CubeSat concept and has given NPS valuable experience in developing CubeSats.   The program management and construction of the prototype solar cell testing satellite has been documented in this thesis and can be used as a guide for future CubeSat projects.

APPENDIX

A. SOLAR PANEL CONSTRUCTION WITH TASC SOLAR CELLS

Required Equipment:

Solar cells-Spectrolab improved triple junction triangular shaped TASC solar cells. We can fit about 20 solar cells per side.

Isopropyl alcohol-Recogent grade Isopropanol 99.8%

Chem wipe-Kimberly-Clark Kimwipes EX-L

Compressed air-Aero-Duster MS-222N

Solder paste-Kester Type R500 Cat # 57-3901-5603

Hot plate-Cold Flow Model GF-SL

Heat gun-Steinel Model HL2010E

Stop watch

Flux Remover-Safezone Solvent & Flux Remover MS-990/CO2

Wire wrap wire-30 Gauge, tin coated

Wire cutters-

Wire solder-Tin/Lead, 60/40

Soldering iron-Pace MBT 350

Solar panel holder-Holder created by the 3D printer or vise

Heat stripper-Patco Model PTS-30

Red and black wires-24 Gauge Alpha 5854/7

Flux-Kester Flux Pen #186

Microscope-Luxo

Multimeter-Mastech, MY64

Procedures:

Procedure 1: Inspect and test the solar cells.

Step 1: Inspect the solar cells and ensure there are no cracks, stress marks or point defects. Set aside cells with defects.

Step 2: Test each TASC solar cell with a multimeter. Set aside cells that are electrically defective.

NOTE: Although no electrically defective TASC solar cells were encountered at NPS, other developers have encountered TASC solar cells that do not work.

Procedure 2: Prepare the substrate.

Step 1: Using isopropyl alcohol and a chem wipe to clean substrate.

Step 2: Dry with Aero Duster

Procedure 3: Solder cells to plate.

Step 1: Turn on hot plate. It should be set to heat up to 180 deg C.

Step 2: Apply solder paste to substrate (Caution: Do not apply too much solder, it may cause a short circuit.) There is a wide range of solder patterns that work on the smaller cells. One thin line the length of the cell or two to five small dots evenly spaced should be plenty. If there is hardened solder already on the substrate, remove it with solder wick prior to re-soldering the cell to the substrate. Attempt to solder four to five cells each cycle.

Step 3: Place cell on the substrate. Ensure the cell matches up with the substrate exactly. If you put the cell on crooked, it will set crooked.

Step 4: Study the solder paste profile. The paste will liquefy at just over 180 deg C. The solder should be in the reflow zone for a maximum of 90 seconds. Complete the cells between two to four minutes after the panel is put on the hot plate.

Step 5: Ensure the hot plate is 180 deg C. Put the panel (solar cell face up) on the hot plate. Start the clock.

Step 6: After one minute turn on the heat gun to allow it to warm up.

Step 7: After two minute apply heat to the solar cell from the heat gun at 480 deg F. Ensure the tip of the heat gun is about an inch from the cell. Keep the heat gun moving back and forth, evenly heating the cell, then concentrate on the larger end and wait for the reflow. When the temperature of the solder gets to the reflow zone, flux will pour out from under the cell as it separates from the solder. At this point, any solder that was visible should be sucked under the cell. Once this happens at the larger end, slowly transfer the heat to the other end, and it should flow as well.

Step 8: Continue to heat solar cells until all cells are complete or the clock reaches four minutes.

Step 9: With tweezers remove the panel from the hot plate. Turn the heat gun to cool and turn off when cooled down to 120 deg F. Repeat steps 2 through 9 until solar panel is completely populated with solar cells.

Step 10: Wash flux off cells and panel with flux remover and isopropyl alcohol. Dry with Aero-Duster.

Procedure 4: Solder the pad of each cell to its corresponding pad on the board.

Step 1: Set panel in a stable holder and poke the wire into the hole in the pad on the panel. Ensure the wire is stable in the hole and the wire is perpendicular to the board.

Figure 19.   15:1 scale picture of wire soldered to the pad and solar cell

Step 2: Solder wire to pad on the panel.

      a. Set the soldering iron to 850 deg F.

      b. Apply heat to the panel pad and wire and touch solder wire to the pad where the wire is inserted. The solder should melt and adhere to the pad.

      c. Remove the solder wire and soldering iron tip.

Step 3: Snip wire to required length of approximately 3 mm.

Step 4: Bend wire over to solar cell pad. The wire should not extend beyond the pad, and it should extend at least one-quarter of the way across the pad. The wire should be touching the pad.

Step 5: Solder wire to pad on solar cell.

      a. Set the soldering iron to 850 deg F.

      b. Apply heat to the solar cell pad and wire and touch solder wire to the pad where the wire is laying. The solder should melt and adhere to the pad.

      c. Remove the solder wire and soldering iron tip.

      Note: The solder on the panel pad will reflow, but if the wire was stuck in the hole and the wire is not pushed too much, the wire should stay in place.

Step 6: Evaluate quality of solder job. If pad is not fully covered in solder or it is uneven, reapply solder. If the wire is no longer in the hole, reflow the solder on both pads and remove the wire. Use solder wick to remove the solder on the pad on the panel, but NOT the solar cell pad. Use of solder wick on the solar cell pad could remove the silver coating.

Step 7: Test all connections to ensure no short circuits

Step 8: Wash flux off cells and panel with flux remover and isopropyl alcohol. Dry with Aero-Duster.

Procedure 5: Attach wires to panel.

Step 1: Cut number of red and black wires to fit your board (one red and one black for each string of solar cells) length ~ one foot. This length can be adjusted later to fit the design.

Step 2: Remove the insulation from each end of each wire with a heat stripper (remove approximately 4-8mm)

Step 3: Tin the end of each wire. (Use solder to strengthen the ends to prevent fraying)

Step 4: Carefully study the wiring of the panel to ensure connecting the correct wire to the hole.

Step 4: Stick the wire into the hole of the panel. Ensure the end extrudes no more than 2mm through the hole. Solder the wire to the hole. Ensure the connection is strong with a slight tug.

Step 5: Test all connections to ensure no short circuits.

Step 6: Wash flux off cells and panel with flux remover and isopropyl alcohol. Dry with Aero-Duster.

Procedure 6: Solder temperature sensors to panel.

Step 1: Prepare area to be soldered with flux.

Step 2: Using magnification, such as the Luxo microscope, solder each leg of the temperature sensor to its corresponding solder pad.

>   **NOTE**:   Magnification is required because of the extremely small size of the temperature sensor solder points.

Step 3: Wash flux off cells and panel with flux remover and isopropyl alcohol. Dry with Aero-Duster.

B. THERMAL VACUUM CHAMBER OPERATION

The thermal vacuum chamber is designed to test equipment under a vacuum and beyond the temperatures expected in the space environment. The chamber is capable of reducing the pressure to less than $1 \bullet 10^{-5}$ Torr. One Torr is equivalent to $\frac{1}{760}$ of an atmosphere or one mm of mercury in a barometer. All pressures in the chamber are reported in Torr.

<u>Required Equipment:</u>

Thermal vacuum chamber-plugged into 110V power strip

Turbo molecular pump-plugged into 110V power strip

Roughing pump-plugged into 110V power strip

Test equipment-Equipment to be tested in the Thermal vacuum chamber

DB50 connection-required if taking readings from equipment during test

DB25 connection-required if taking readings from equipment during test

DB15 connection-required if taking readings from equipment during test

<u>Procedures:</u>

Procedure 0: Prepare DB50 and DB25 connectors. (if taking electrical readings during the thermal vacuum testing)

> Step 1: Connect the component to be tested to the DB50 connector. Pins 1 through 10 on the DB50 connect to pins 1 through 10 on the DB15. Pins 11 through 35 on the DB50 connect to pins 1 through 25 on the DB25.
>
> Step 2: Connect measuring tool (oscilloscope, multimeter) to DB15 and DB25 found on top of the thermal vacuum chamber.
>
> Note: DB50 does not directly correspond to DB 25. DB50 = DB25 + 10. Pins 11-35 on DB50 connect to Pins 1-25 on DB25.

Procedure 1: Prepare the thermal vacuum chamber.

Step 1: Ensure thermal vacuum chamber is clean on the inside.

Step 2: Ensure thermocouples are intact.

Procedure 2: Prepare the tested equipment.

Step 1: Clean all surfaces of the tested equipment.

Step 2: Place the test equipment into the thermal vacuum chamber ensuring no wires or protrusion cross the seal. Ensure the tested equipment does not rest on a wall.

Note: Equipment touching a chamber wall will lead to uneven cooling and heating.

Step 3: (if required) Electrically connect satellite component to DB50 within the Chamber.

Step 4: (if required) Connect test equipment to DB25 on top of thermal vacuum chamber.

Note: DB50 does not directly correspond to DB 25. DB50 = DB25 + 10. Pins 11-35 on DB50 connect to Pins 1-25 on DB25.

Procedure 3: Seal the thermal vacuum chamber.

Step 1: Ensure the seal is clear of all wires, protrusions, dust and any debris.

Caution: Any debris on the seal may bridge the seal causing leaks and diminishing the effectiveness of the thermal vacuum chamber.

Step 2: Seal both doors of the thermal vacuum chamber.

Note: The outer door has no effect on the pressure of the chamber.

Procedure 4: Power up the thermal vacuum chamber.

Step 1: Turn on 110V power strip underneath the thermal vacuum chamber. Audibly verify that the fan is spinning.

Step 2: Flip MAIN POWER switch on (black switch on the top right).

Note: The MAIN POWER switch allows temperature control.

Step 3: Turn on the roughing pump by flipping the switch on the top-left side of the roughing pump underneath the thermal vacuum chamber.

Caution: Never turn off the roughing pump until the pressure is at least 200 Torr. Doing so can create a suction, drawing the lube oil out of the pump into the chamber.

Note: The pressure can be monitored on the black box on top of the thermal vacuum chamber labeled 340 vacuum gauge controller. The middle display is the pressure of the chamber.

Step 4: Turn on the turbo molecular pump by depressing the on/off button on the box on top of the thermal vacuum chamber labeled Turbo V200. Once the chamber vacuum is at 2×10^{-1} Torr, this pump will automatically turn on.

Step 5: Turn on cold trap to lower the pressure further.

Procedure 5: Heat up the thermal vacuum chamber.

Step 1: Turn on HEAT and DOOR HEAT switches on the right side.

Step 2: Adjust set point to desired temperature. To raise the temperature, push the knob in, twist to the right and release to set.

Note: The temperature set at the display reads the temperature of the chamber wall which is slightly different from the temperature inside the chamber. The temperature inside the chamber can be monitored by looking at the Wahl Thermocouple display on top of the thermal vacuum chamber. There are up to five thermocouples to choose from. All temperature readings are in Celsius.

Procedure 6: Cool down the thermal vacuum chamber.

Step 1: Ensure HEAT and DOOR HEAT are turned off.

Step 2: Turn on AMBIENT COOLING.

Step 3: Once less than 0 degrees Celsius, turn off AMBIENT COOLING and turn on SUB-ZERO COOLING.

Caution: Using both AMBIENT COOLING and SUB-ZERO COOLING will freeze the lines within the thermal vacuum chamber.

Step 4: Adjust set point to desired temperature. To lower the temperature, push the knob in, twist to the left and release to set.

Note: The temperature set at the display reads the temperature of the chamber wall which is slightly different from the temperature inside the chamber. The temperature inside the chamber can be monitored by looking at the Wahl Thermocouple display on top of the thermal vacuum chamber. There are up to five thermocouples to choose from. Note: All temperature readings are in Celsius.

Procedure 7: Recompress the thermal vacuum chamber.

Step 1: Ensure HEAT, DOOR HEAT, COOLING and SUB-ZERO COOLING are all off and the temperature set point is 20C.

Step 2: Slightly open vent.

Step 3: Open main nitrogen gas valve and maintain pressure at ten psi on the left gauge.

Step 4: Slightly open small black nitrogen gas valve (at the exit of the left gauge).

Step 5: Monitor the rise in pressure at the 340 vacuum gauge controller, and control the rise by opening the vent more.

Step 6: At 200 Torr turn off the roughing pump by flipping the switch on the top-left side of the roughing pump underneath the thermal vacuum chamber.

Step 7: At approximately 760 Torr shut off gas and close vent.

Step 8: Once temperature is ambient, turn off MAIN POWER.

Step 9: Turn off 110V power strip.

Step 10: Open the chamber.

C.   SAMPLE CUBESAT LINK BUDGET

This link budget was developed by David Rigmaiden using 560km altitude.

Item	Units	Down Link			Up Link				
Orbit Altitude	km	560	560	560	560	560	560		
Spacecraft Elevation Angle	deg	10	45	89.99	10	45	89.99		
Frequency	GHz	2.44	2.44	2.44	2.44	2.44	2.44		
Wavelength	m	0.123	0.123	0.123	0.123	0.123	0.123		
Propagation Path Length	km	1839.27	762.30	560.00	1839.27	762.30	560.00	SMAD p. 110-115	
Space Loss - Ls	dB	-165.48	-157.83	-155.15	-165.48	-157.83	-155.15		
System Noise Temperature - Ts	k	585	585	585	585	585	585	SMAD p. 556-558	
Bit Error Rate		1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05	1.00E-05		
Required Eb/No for BER 10-5	dB	13.5	13.5	13.5	13.5	13.5	13.5	SMAD p. 562	
Data Rate - Rb	kbps	115.2	115.2	115.2	115.2	115.2	115.2		
Symbols Per Bit		1	1	1	1	1	1	SMAD p. 559	
Symbol Rate - Rs	kbps	115.2	115.2	115.2	115.2	115.2	115.2		
ro		1.50	1.50	1.50	1.50	1.50	1.50		
Required C/No	dB	64.11	64.11	64.11	64.11	64.11	64.11	$E_b/N_o+10*\log(R_b)$	
Bandwidth - BW	MHz	0.288	0.288	0.288	0.288	0.288	0.288	$(1+ro)*R_s$	
Required C/N	dB	9.52	9.52	9.52	9.52	9.52	9.52	$C/N_o-10*\log(BW)$	
Receiver Bandwidth - B	MHz	0.4	0.4	0.4	0.4	0.4	0.4		
GND Antenna Diameter	m	3.04	3.04	3.04	3.04	3.04	3.04		
GND Antenna Feed Efficiency	%	55	55	55	55	55	55		
GND Antenna Half Power Beamw	deg	2.83	2.83	2.83	2.83	2.83	2.83	SMAD p. 571	
GND Antenna Pointing Error	deg	2.0	2.0	2.0	2.0	2.0	2.0		
GND Antenna Pointing Error Loss	dB	-7.65	-7.65	-7.65	-7.65	-7.65	-7.65		
GND Antenna Gain - G	dBi	37.81	37.81	37.81	37.81	37.81	37.81		
S/C Antenna Diameter	m	0.0392	0.0392	0.0392	0.0392	0.0392	0.0392		
S/C Antenna Feed Efficiency	%	90	90	90	90	90	90		
S/C Antenna Half Power Beamwi	deg	360.00	360.00	360.00	360.00	360.00	360.00	SMAD p. 571	
S/C Antenna Pointing Error	deg	0.0	0.0	0.0	0.0	0.0	0.0		
S/C Antenna Pointing Error Loss	dB	0.00	0.00	0.00	0.00	0.00	0.00		
S/C Antenna Gain - G	dBi	0.01	0.01	0.01	0.01	0.01	0.01		
Transmitter Power	Watts	1	1	1	10	10	10		
Transmitter Power - P	dBW	0.00	0.00	0.00	10.00	10.00	10.00		
Transmitter Line Loss - Ll	dB	-0.5	-0.5	-0.5	-1	-1	-1		
Transmitter Feed Loss - La	dB	-0.46	-0.46	-0.46	-2.60	-2.60	-2.60		
Transmitter EIRP	dBW	-0.94	-0.94	-0.94	44.21	44.21	44.21	$EIRP=P+L_l+G_a+L_a$	
Transmission Path Losses - La	dB	-0.50	-0.50	-0.50	-0.50	-0.50	-0.50		
Receiver Polarization Loss - L	dB	-3	-3	-3	-3	-3	-3		
Receiver Line Loss - La	dB	-1	-1	-1	-0.5	-0.5	-0.5		
Receiver Feed Loss - La	dB	-2.60	-2.60	-2.60	-0.46	-0.46	-0.46		
Receiver LNA Gain	dB	17.00	17.00	17.00	0.00	0.00	0.00		
Received Carrier Power - C	dBW	-126.37	-118.72	-116.04	-133.37	-125.72	-123.04	$C=EIRP+L_s+L_a+G$	
Total Received Noise Power -	dB	-144.91	-144.91	-144.91	-144.91	-144.91	-144.91	$N=k*T_s*B$	k=1.38E-23
Received Carrier To Noise Ratio -	dB	18.54	26.19	28.87	11.54	19.19	21.87	SMAD p. 550-556	
Received Energy Per Bit - Eb	dB	-176.98	-169.33	-166.65	-183.98	-176.33	-173.65	$E_b=C/R_s$	
Received Noise Spectral Density	dB	-200.93	-200.93	-200.93	-200.93	-200.93	-200.93	$N_o=k*T_s$	
Calculated Eb/No	dB	23.95	31.60	34.28	16.95	24.60	27.28		

D.   SCHEDULE AND BUDGET SPREADSHEET DETAILS

NPS-SCAT Budget FY2008

	Oct	Nov	Dec	Jan	Feb	March	April	May	June	July	August	Sept	Yearly Total	Target (Set at beginning of year)
Travel	0.00	0.00	0.00	0.00	0.00	0.00	1,479.97	0.00	0.00	3,600.81	3,505.20	0.00	8,585.98	7,000.0
Faculty / Staff							582.70			0.00	1,698.36	0.00	2,281.06	4,200.00
Jim							582.70			0.00	1,698.36			
Students							897.27			3,600.81	1,806.84	0.00	6,304.92	2,800.00
Alex							328.53			1,709.96	1,806.84			
Rod										1,890.85				
Christina							418.80							
Mark							189.94							
Equipment & Supplies	1,778.00	7,991.24	10,243.00	154.17	0.00	1,672.12	0.00	1,322.12	821.57	2,761.70	1,147.04	0.00	27,890.96	29,476.9
a) E&S less than $15k	1,778.00	7,991.24	9,585.00	154.17	0.00	1,672.12	0.00	1,322.12	821.57	2,103.70	123.55	0.00	25,551.47	25,000.00
Demonstration cube	1,778.00													
EPS(Clyde Space)		4,010.00												
TASC Cells (Spectrolab)		617.24												
Sun Sensor (Sinclair)		2,639.00		11.99										
Linnear EPS (Pumpkin)		725.00												
Cubesat Kit(Pumpkin)			9,585.00											
Chassis/430dev(Digiworks				142.18										
Solid cover plate(2)						690.00								
Exp panel circuitry						427.27								
Exp Solar panel PCB						426.85								
Temperature Sensors						128.00								
SMS supplies(Digikey)								286.99						
Breadboard(Jameco)								280.51						
Tools(Digikey)								315.77						
Tools(Jameco)								438.85						
D Connector(Newark)									85.76					
Power Solar panel PCB									476.98					
Power Solar cells									258.83					
SUN Lamp										269.95				
Pumpkin Clip Set										670.00				
Power Supply										534.56				
Temp sensors(Maxim)										57.20				
Electronics(Jameco)										360.50				
Electronics(Digikey)										211.49				
USB-SPI interface adapter											123.55			
Misc E&S						0.00	0.00		0.00				0.00	0.00
b) E&S greater than $15k													0.00	0.00
c) Software and support	0.00	0.00	658.00	0.00	0.00	0.00	0.00	0.00	0.00	658.00	0.00	0.00	1,316.00	3,476.94
Crossworks			658.00											
Crossworks										658.00				
Misc Software								0.00						
d) Miscellaneous							0.00	0.00	0.00		1,023.49	0.00	1,023.49	1,000.00
Indirect Cost	561.67	2,524.43	3,235.76	48.70	0.00	528.22	467.52	417.66	259.53	2,009.92	1,469.64	0.00	11,523.06	11,523.0
Total Expenses	2,339.67	10,515.67	13,478.76	202.87	0.00	2,200.34	1,947.49	1,739.78	1,081.10	8,372.43	6,121.88	0.00	48,000.00	48,000.0
Actual Cumulative Expenses	2,339.67	12,855.34	26,334.11	26,536.98	26,536.98	28,737.32	30,684.81	32,424.59	33,505.70	41,878.12	48,000.00	48,000.00		
Uniform Burn rate	4,000.00	8,000.00	12,000.00	16,000.00	20,000.00	24,000.00	28,000.00	32,000.00	36,000.00	40,000.00	44,000.00	48,000.00		

Travel Notes:

	Per person	# people	Est cost	Actual cost	Per person
April 2008 CubeSat Developers Workshop	500	4	2000	$1,439.97	$359.99
9-10July 2008 Navy SERB	1700	2	3400	$3,600.81	$1,800.41
9-14Aug 2008 Small Sat	1800	3	5400		
Total			10800	$5,040.78	

Small Sat estimate cost
Per Diem: 54/ day(5 1/3 days)=$288
Driving: $.485/mile *288 miles=$140* 2 cars= $280
Hotel:105/night*2=$210+135/night*2=210+270=$480
Registration: $150+40*3=270
Total=$1318

Expected vs Uniform Expense Burn Rate ($)

NPS-SCAT Budget

- Travel — 8,585.98
- Equipment — 25,551.47
- Software — 1,316.00
- Miscellaneous — 1,023.49
- Indirect Cost — 11,523.06

NPS-SCAT Schedule FY2008

		Q1	**Q2**	**Q3**	**Q4**
MIlestones					
Requirements review		x			
Design review #1 (prior to COTS hardware buy)		x			
Design review #2 (prior to hardware build)			x		
Design review #3 (prior to integration and test)				x	
Phase 2 proposal development			x		
Phase 2 proposal submission			x		
Prototype Build Complete					x
Final Report					x
Tasks					
Requirements definition		x	x	x	x
Budget refinement		x	x	x	x
Schedule refinement		x	x	x	x
Phase 2 Requirements definition				x	x

COTS hardware & software selections		Purchase info	Q1				
COTS hardware & software selections		Purchase info	x				
1U-CubeSat (Skel) Kit	Pumpkin	$6,000 x	x				8RCRRL01
CubeSat Solar Panel Clip Set	Pumpkin	$450 x	x				8RCRRL01
CrossWorks Development Software (2 at $329 each)	Rowley Ass.	$658 x	x				8RQRRLXX
CubeSat Skeletonized structure	Pumpkin	$1,778 x	x				8RQRRL01 (21OCT07)
CubeSat Power		$7,425		x			
CubeSat COMM		$3,045		x			
Payload (Solar Cell Measurement System)		$4,621			x	x	
TOTAL Hardware		$24,454	$20,190				

Purchase History	Order Number	Date	PR Cost	DORS		Month	EQPT	Software	Travel	Total	Shipping
Demonstration cube	8RQRRL01	23-Oct-07	$1,745.00	$1,778.00	r	OCT	1778.00	0.00	0.00	1778.00	$33.00
EPS(Clyde Space)	8RCRRL09	15-Nov-07	$3,815.00	$4,010.00	r	NOV	7991.24	0.00	0.00	7991.24	$195.00
TASC Cells (Spectrolab)	8RQRRL02	15-Nov-07	$600.00	$617.24	r	DEC	9585.00	658.00	0.00	10243.00	$17.24
Sun Sensor (Sinclair)	8RQRRL06	15-Nov-07	$2,500.00	$2,639.00	r	JAN	154.17	0.00	0.00	154.17	$139.00
Crossworks	8RQRRLXX	21-Nov-07	$658.00	$658.00	r	FEB	0.00	0.00	0.00	0.00	$0.00
Linnear EPS (Pumpkin)	8RQRRL05	28-Nov-07	$695.00	$725.00	r	MAR	1672.12	0.00	0.00	1672.12	$30.00
Cubesat Kit(Pumpkin)	8RCRRL01	20-Dec-07	$9,585.00	$9,585.00	r	APR	0.00	0.00	1519.97	1519.97	$0.00
Chassis/430dev(Digiworks)	8RQRRL07	8-Jan-08	$59.90	$142.18	r	MAY	1322.12	0.00	0.00	1322.12	$82.28
Fed Ex (Sinclair)	8RQRRL08	24-Jan-08	$20.00	$11.99	r	JUN	821.57	0.00	0.00	821.57	-$8.01
Coverplate(solid)	8RQRRL10	12-Mar-08	$650.00	$690.00	r	JUL	2103.70	658.00	6108.65	8870.35	$40.00
Office Supplies	SSAG OPTAR	20-Mar-08	$217.73	$0.00	r	AUG	0.00	0.00	3539.90	3539.90	
Exp panel circuitry	8RQRRL11	24-Mar-08	$420.84	$427.27	r	SEP	0.00	0.00	0.00	0.00	$6.43
Exp panel PCB	8RQRRL13	27-Mar-08	$411.10	$426.85	r	TOTAL	25427.92	1316.00	11168.52	37912.44	$15.75
Temperature Sensors	8RQRRL12	31-Mar-08	$118.00	$128.00	r						$10.00
Travel Christina(CalPoly)	8TOSIXFG			$418.80	r						
Travel Mark(CalPoly)	8TOSIXGU			$189.94	r						
Travel Alex(CalPoly)	8TOSJ5KS			$288.53	r						
Travel Jim(CalPoly)	8TOSJ7EA			$542.70	r						
Registration(CubeSat) Alex	8RVRRL01			$40.00	r						
Registration(CubeSat) Jim	8RVRRL02			$40.00	r						
SMS supplies(Digikey)	8RQRRL14	13-May-08	$276.23	$286.99	r						$10.76
Breadboard(Jameco)	8RQRRL15	13-May-08	$256.54	$280.51	r						$23.97
Tools(Digikey)	8RQRRL17	30-May-08	$295.57	$315.77	r						$20.20
Tools(Jameco)	8RQRRL16	30-May-08	$424.11	$438.85	r						$14.74
D Connector for Sun Sens	8RQRRL18	5-Jun-08	$102.52	$85.76	r						-$16.76
TASC Cells (Spectrolab)	8RQRRL19	6-Jun-08	$250.00	$258.83	r						$8.83
Power solar panel PCB	8RQRRL20	6-Jun-08	$411.10	$476.98	r						$65.88
Travel Alex(DC)	8TOT206D			$1,709.96	r						$34.42
Travel Rod(DC)	8TOT3NWR			$1,890.85	r						
Travel Alex(UTAH)	8TOTA8NZ			$1,506.84							
Travel Rod(UTAH)	DNA			$0.00							
Travel Jim(UTAH)	8TOT97TA			$1,001.00							
Travel Jim(UTAH)	8TOT97TA			$732.06							
Registration(Small Sat)	8TGRRL26			$300.00							
Pumpkin	8RQRRL23	18-Jul-08	$645.00	$670.00	r						$25.00
Temperature Sensors	8RQRRL21	18-Jul-08	$47.20	$57.20	r						$10.00
Techni-tool, power supply	8RQRRL22	18-Jul-08	$590.00	$534.56	r						-$55.44
Sun Lamp	8RQRRL24	16-Jun-08	$269.95	$269.95	r						$0.00
Crossworks	8RQRRL25	31-Jul-08	$658.00	$658.00							$0.00
Electronics(Jameco)	8RQRRL27	31-Jul-08	$327.30	$360.50	r						$33.20
Electronics(Digikey)	8RQRRL28	31-Jul-08	$180.20	$211.49	r						$31.29
USB-SPI interface(Diolan)	8RQRRL29	7-Aug-08	$98.80	$123.55	r						$24.75
										TOTAL cost	$791.53
			$26,328.09	$26,867.47						Avg cost	$27.29

FY08 Budget	$48,000.00
FY08 Indirect Cost	$11,523.06
FY08 Budget Spent	$26,867.47
FY08 Budget Remaining	$9,609.47
Travel(Prospective)	$8,585.98
Equipment(Prospective)	$1,023.49

E.   SPACECRAFT COMPONENTS

This appendix includes photographs taken of various components of NPS-SCAT.
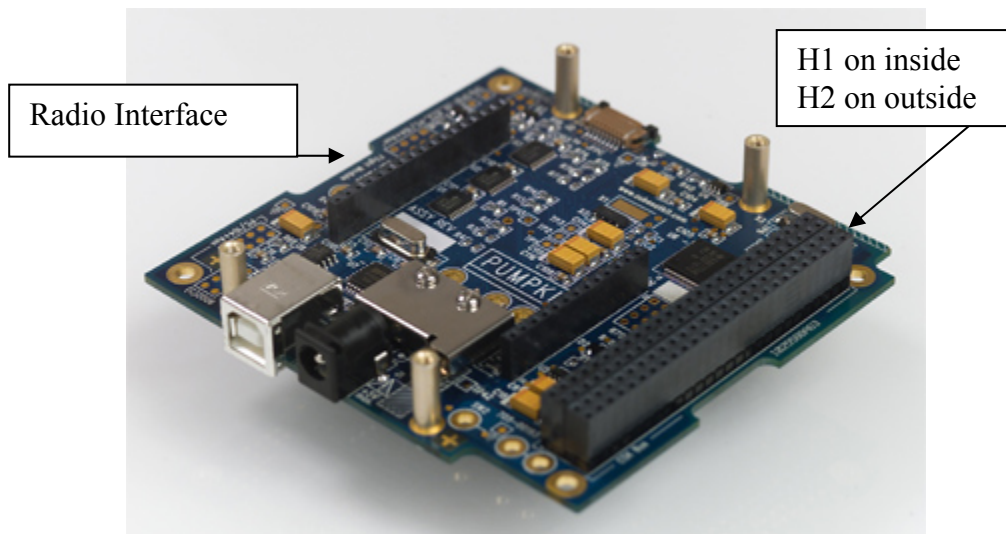

Figure 20.   CubeSat skeletonized structure
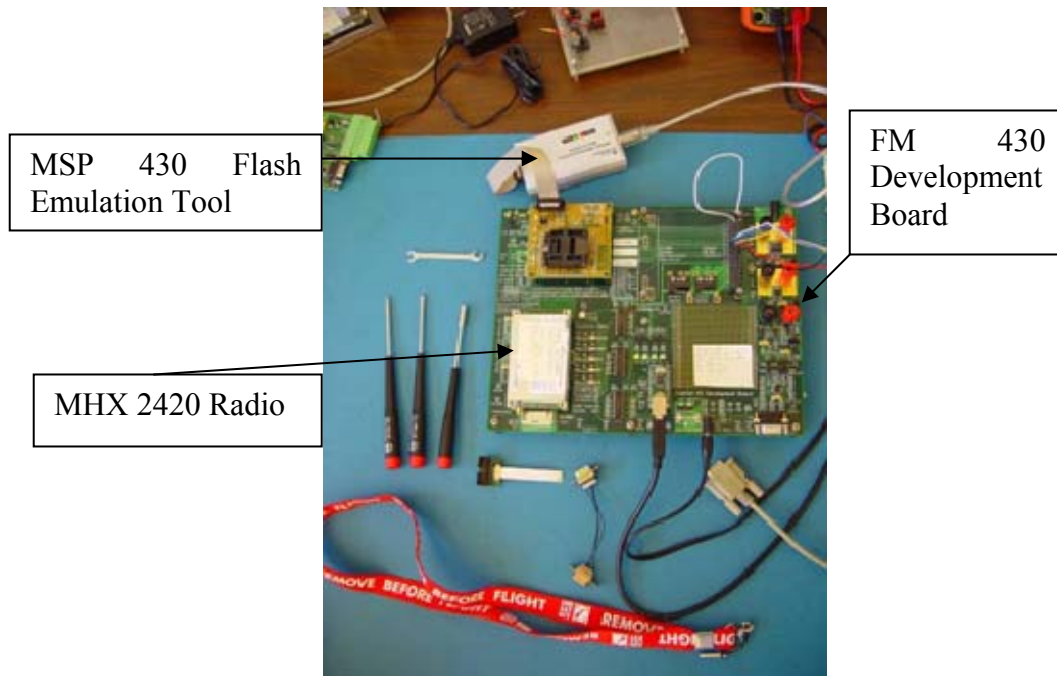

Figure 21.   FM430 Development board

Figure 22.   CubeSat Kit® Components with FM430 Development board, MSP430 Flash emulation tool, and miscellaneous tools, hardware and structural fasteners
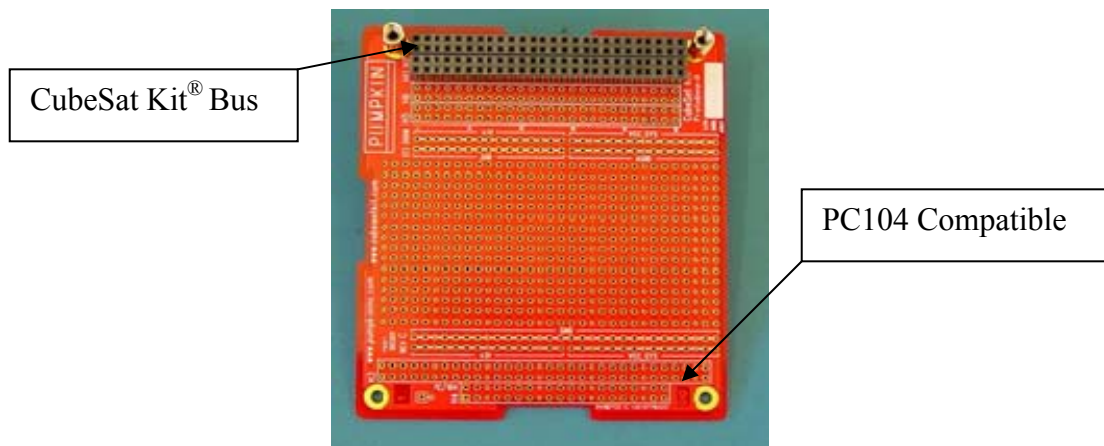

Figure 23.   CubeSat Kit® Protoboard

Figure 24.   MHX 2420 Transceiver

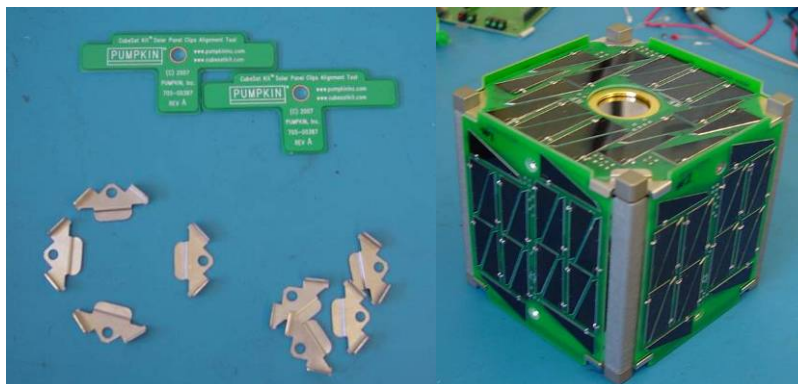Figure 25.   Development Board with Radio

Figure 26.   Pumpkin Solar Panel Clip Set on the Left and Clips Holding Solar
Panels on the Right.

This clip set is designed specifically for the Pumpkin CubeSat Kit®. Each of the
eight clips is held on by a foot. Each solar panel is held in place at each corner by a clip.

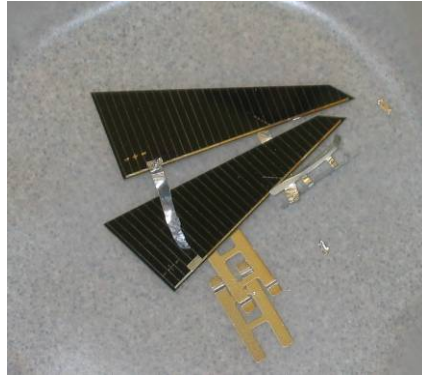Figure 27.   Pumpkin® Linear Power Supply

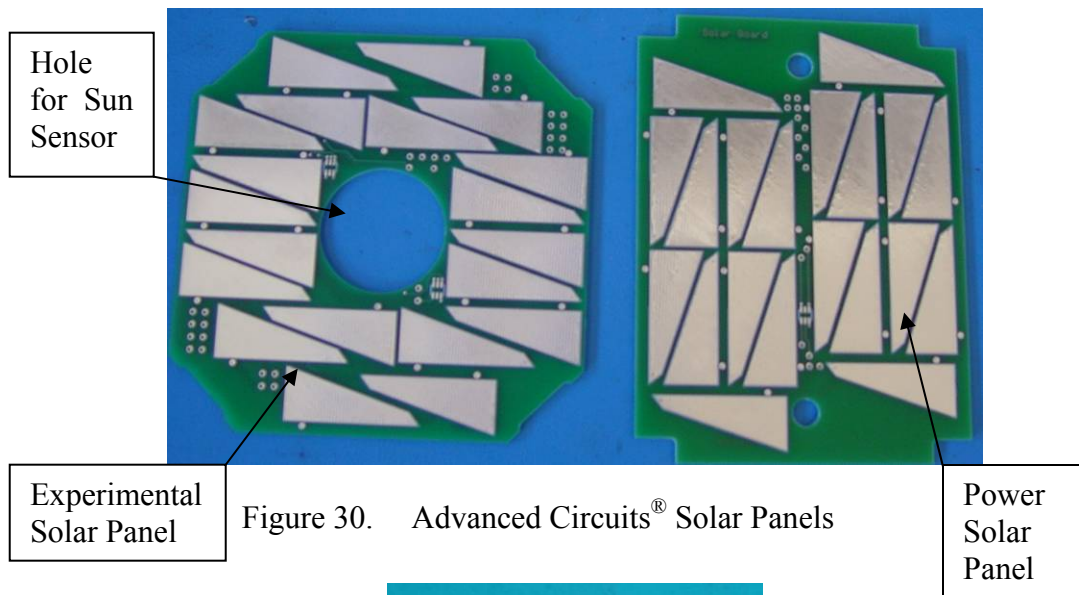Figure 28.   Clyde Space® EPS

Figure 29.   Spectrolab® TASC

Hole for Sun Sensor

Experimental Solar Panel

Figure 30.   Advanced Circuits® Solar Panels

Power Solar Panel

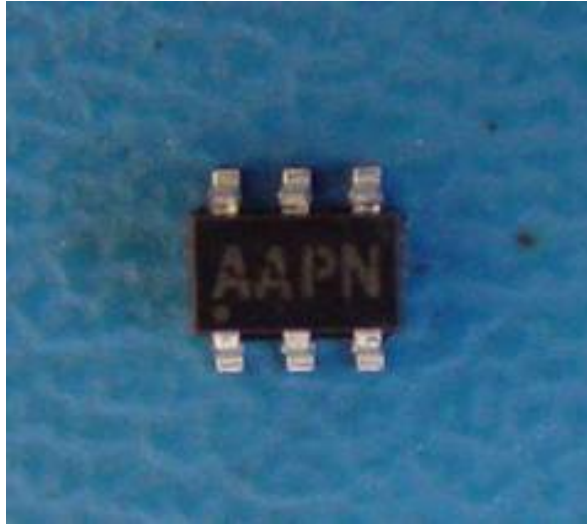Figure 31.   Sinclair® SS411 Digital Sun Sensor in 1:1 scale

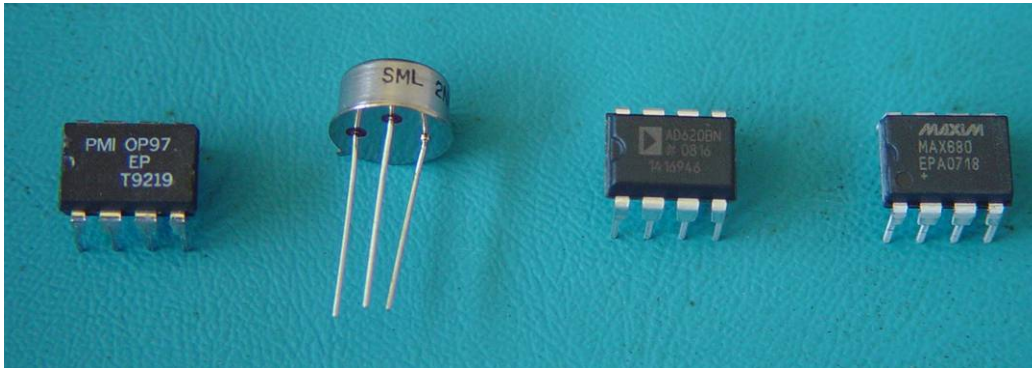Figure 32.   MAX 6630MUT Temperature Sensor (10:1 Scale)

Figure 33.   OP97 OpAmp, 2N6796 MOSFET, AD620 Inst Amp, and
MAX680 Voltage Converter in 2:1 scale

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